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AN INTRODUCTION TO MULTIPLE ACCESS SATELLITE COMMUNICATION

X OTS

(NASA Report No. 5 on Contract No. NASw-495)

S. G. Lutz

~~February~~ 1963 10 p

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HUGHES RESEARCH LABORATORIES
Malibu, California

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AN INTRODUCTION TO MULTIPLE ACCESS SATELLITE COMMUNICATION

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ABSTRACT

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Multiple access, or more specifically, random multiple access, presents advantages with satellite communication not heretofore realizable. Related problems and some solutions are treated to introduce the reader to the subject as well as to stimulate thought. The variety of aspects treated include adaptability of multiple-access systems, orbital constraints with regard to communication coverage and economics, modulation and multiplexing requirements, and possible calling techniques with associated problems. Some conclusions which are tentative and far from definite indicate a preference at this time for the SSB up and FM down FDM modulation configuration, the stationary orbit system, and utilization of a master control type of calling scheme.

AUTHOR

PREFACE

This introductory study of Multiple Access Satellite Communication has been prepared for the National Aeronautics and Space Administration as a part of the studies sponsored by Contract No. NASw-495. The views here expressed are those of the author, Samuel G. Lutz, and should not be interpreted as reflecting the official opinion or policy of NASA, nor of Hughes Aircraft Company.

I. PURPOSE AND INTRODUCTION

This report is intended as an introductory survey of multiple access satellite communication, wherein three or more earth stations sharing the use of a communication satellite can communicate with each other simultaneously. Heretofore, intercontinental or other long-haul communication has been accomplished by establishing a chain of two-terminal "trunk" circuits, such as land lines or microwave relay chains, and submarine cables or HF radio circuits. In contrast, switchboards or "exchanges" have provided direct interconnections, when and as needed, between telephones within "local" areas. In the pre-Sputnik era the concept of the intercontinental exchange, perhaps for the entire Atlantic Basin, seemed too absurd to merit serious study. The cost of surface communication was a function of distance, so only relatively direct circuits could be used. However, for one-hop satellite circuits, cost should be independent of the distances between its earth stations. When several stations use a satellite simultaneously the satellite becomes a nodal point of the system, a point of possible interconnection or perhaps the equivalent of an "exchange in orbit." This concept is clear, as is its possibility of revolutionizing the prior approach to long-haul communication. It is chiefly the "how best to do it" problems which remain vague and in need of clarification.

It is hoped that this report will aid in clarifying the various aspects of and approaches to multiple access in satellite communication so that its readers, after enough further study, can decide "how best to do it."

II. PHYSICAL AND DEFINITIVE ASPECTS OF MULTIPLE ACCESS SYSTEMS

A. Paired-terminal Systems with Surface "Multiple Access"

Though vividly suggestive, an "exchange in orbit" definition of multiple access would be too glib. Instead, we will start by observing that a system lacks multiple access if each satellite is used by not more than two earth stations at a time. Figure 1 is a familiar illustration of such a system, as proposed in July 1960.* In using this illustration it is

*Submission by AT & T to FCC Docket 11866, July 8, 1960, Attachment 7.

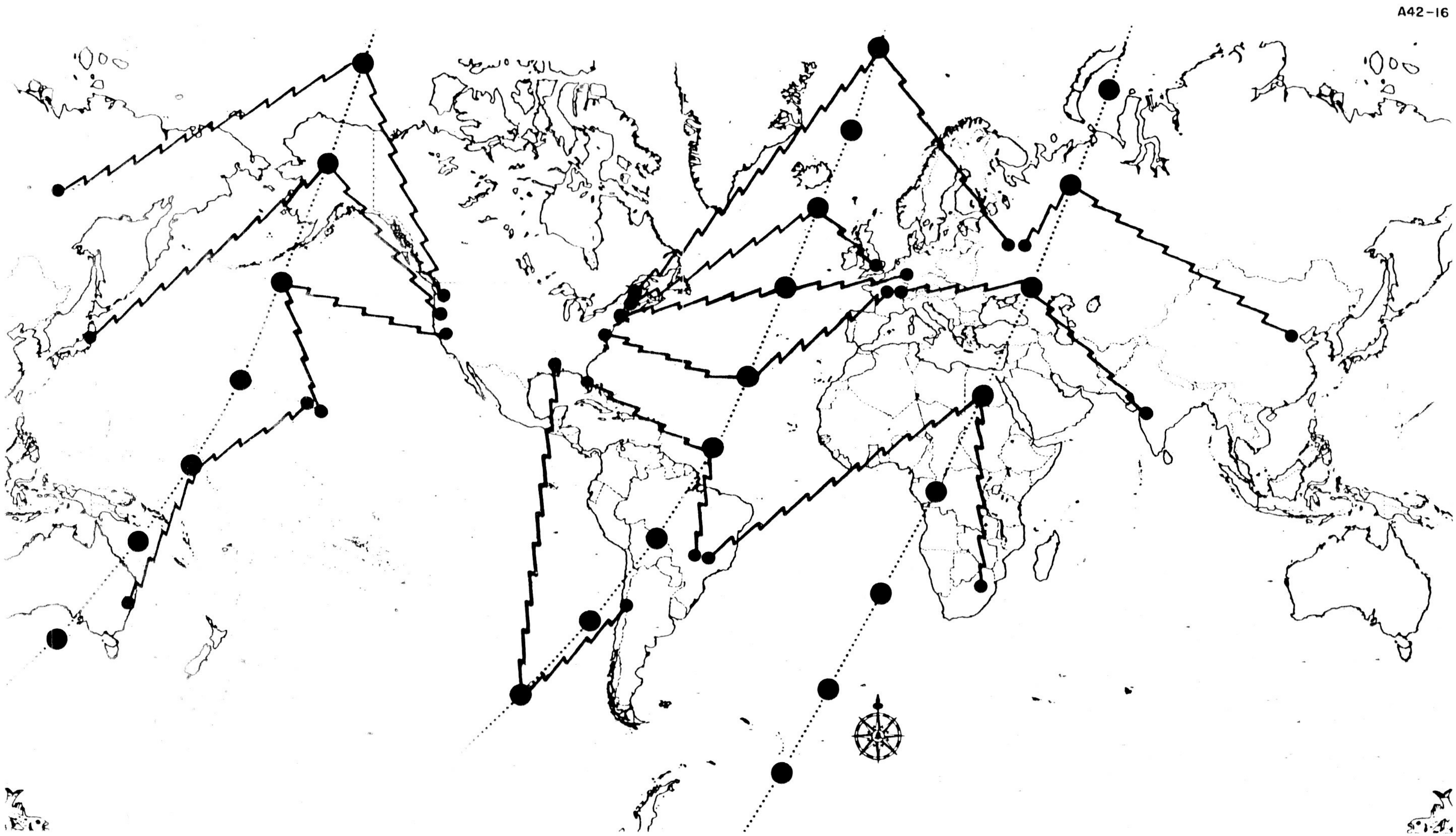

Fig. 1. AT&T proposed random orbit system.

not implied that a system using random-orbit satellites need be incapable of some degree or form of multiple access. This illustration, however, shows only pairs of stations in communication via satellites, much as if joined by cables or other two-terminal circuits.

It has been argued that such a system achieves "multiple access" via the interconnectibility of surface communication systems, which can connect distant cities, even those in other nations, to these satellite stations. True, we have been doing this to submarine cable stations because so many cables direct to scattered population centers is not feasible. Since this surface "multiple access" is neither new nor better, we exclude it and concentrate on multiple access between earth stations and via one or more satellites.

B. Permanent Channel Multiple Access

It is frequently proposed that channels of some form through the satellite be provided permanently from each station to every other station which shares use of the satellite. By way of illustration (see ref. 1), Fig. 2 shows stations in North and South America, Europe, and Africa sharing use of a stationary satellite. Figure 3 shows that each might be assigned a band of transmitting frequencies proportionate to its needs. Each such band would be further divided into sub-bands for transmissions to the other three stations. Collectively, they all form a frequency division multiplex occupying the satellite's receiving band. After frequency translation and retransmission by the satellite, each station receives the entire band but selects via filters only those three sub-bands being transmitted to it.

It will be seen that systems of this permanent channel class have considerable merit so long as (1) there are few stations in the system, and (2) traffic between each station pair is relatively uniform and within the capacity of its sub-band. Of course, one could sophisticate such a system by placing it under a "master control," able to reallocate the widths of the sub-bands in accordance with traffic needs.

Figure 4 extends this approach to six stations, requiring 15 two-way, or 30 one-way circuits to connect all possible pairs of stations. Generalizing, N stations would require N (N-1) one-way circuits, becoming nearly N^2 when N is large. For 30 stations, the satellite frequency channel would need to be chopped into 870 such sub-bands, whereas the satellite's total capacity might be, say, only 1000 one-way voice channels. Hence, there could be two conversations at a time between 65 station pairs, but not more than one at a time between the remaining 370 station pairs. Clearly, the normal utilization of the satellite's capacity would be extremely low and the ability to handle the unexpected peak loads between station pairs would be very poor. One would prefer the flexibility of a telephone switchboard.

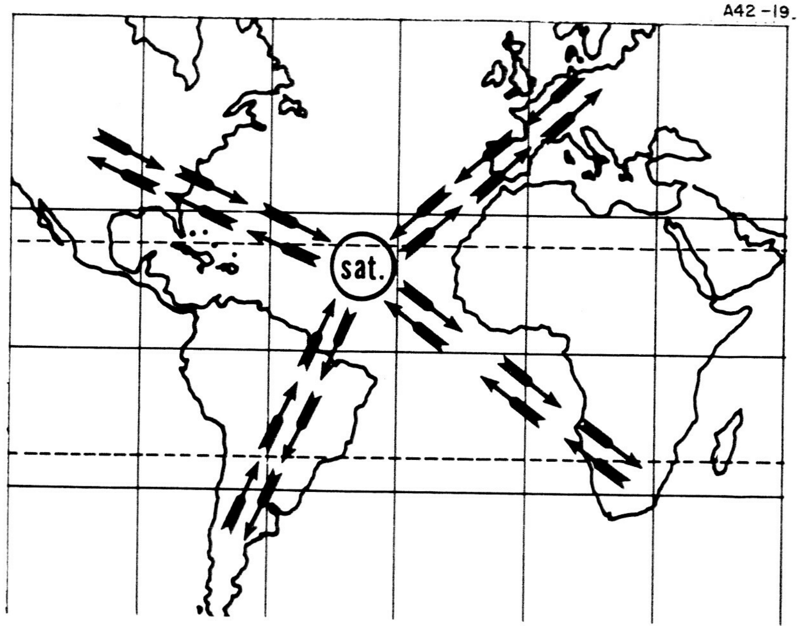

Fig. 2. Coverage with Atlantic stationary satellite.

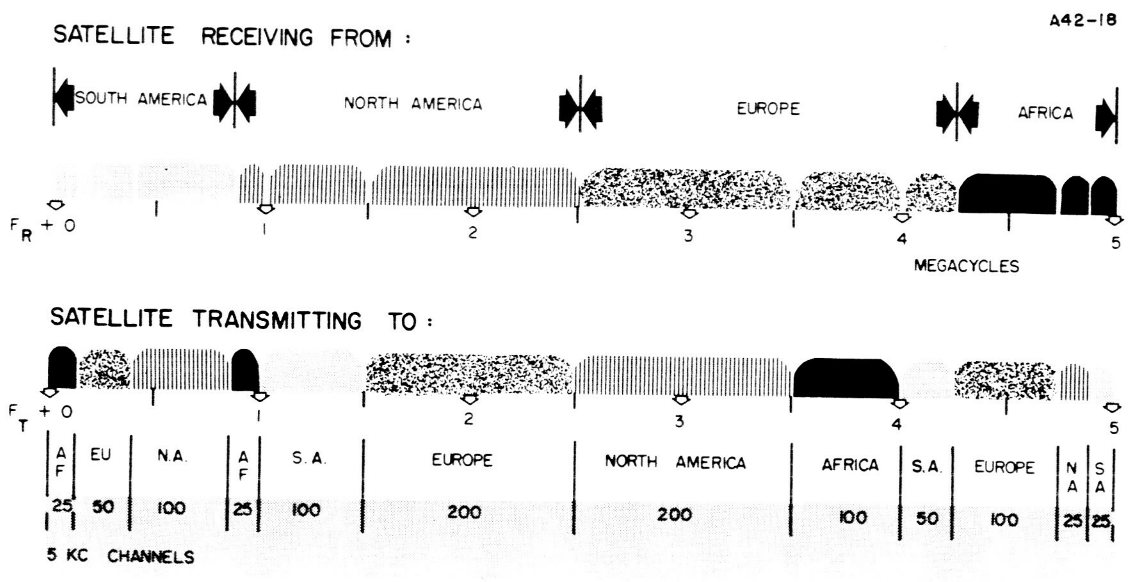

Fig. 3. Illustrative band — allocations for Atlantic satellite of Fig. 2.

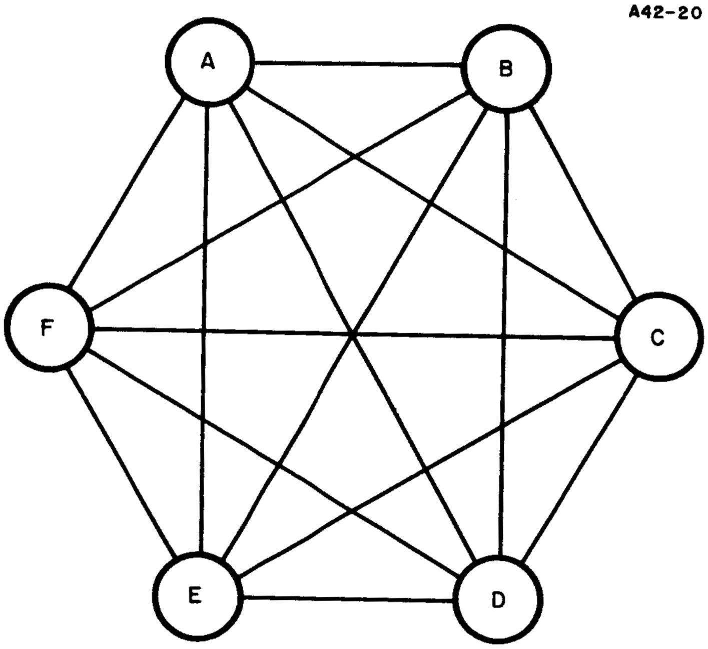

Fig. 4. Possible interconnections between six stations

Before leaving the discussion of such systems, one observes that the need for connection of certain station pairs might be too low to justify permanent channels. Or one may contemplate a "chain of command" system with a tree of links as shown in Fig. 5. Here there are 40 stations connected by only 39 two-way links. Such a tree would better utilize the satellite's capacity but in exchange for its constraint of communication to "normal" channels of command between adjacent command levels. Planners of such systems have also been known to propose "full multiple access" by the expedient of "patching" these circuits (or relaying) at the nodes. Figure 6 shows that such a patched path between stations 9 and 10 passes through the <u>same</u> satellite six times. With a stationary satellite, the round trip or pause-to-reply delay would exceed three seconds and approach moon-bounce delays! Again, one would prefer the flexibility of a telephone switchboard, especially recognizing that certain of its circuits could be left interconnected, like leased circuits or "hot lines."

C. Random Multiple Access

IT & T engineers and perhaps others, have proposed the prefix "random" to categorize the switchboard type of multiple access, with which each station can call and communicate with other stations "at random," whenever and so long as needed, but not exceeding its allocated share of the satellite's channel capacity. A further prefix "<u>controlled</u> random multiple access" categorizes systems incorporating a "master control" station which allocates channels as needed, to better utilize the satellite's capacity. With "tight control," each station calls master control for the allocation of each channel as it is needed. With "loose control", stations are allocated groups of channels for use as needed, but with the number of channels in each station's group being periodically adjusted by master control to accommodate fluctuations of the system's traffic pattern and thus making better use of the satellite's capacity. Tight and loose control will be discussed subsequently in connection with calling and channel allocation techniques.

Obviously, random multiple access cannot start with a true automatic switchboard in the satellite; it may never reach this extreme. Early satellites must be kept simple with little or no "signal processing" required beyond frequency translation and perhaps a simple change of modulation, such as from multiplexed SSB to FM. This can be accomplished by placing the switching function with the earth stations, as will also be discussed subsequently.

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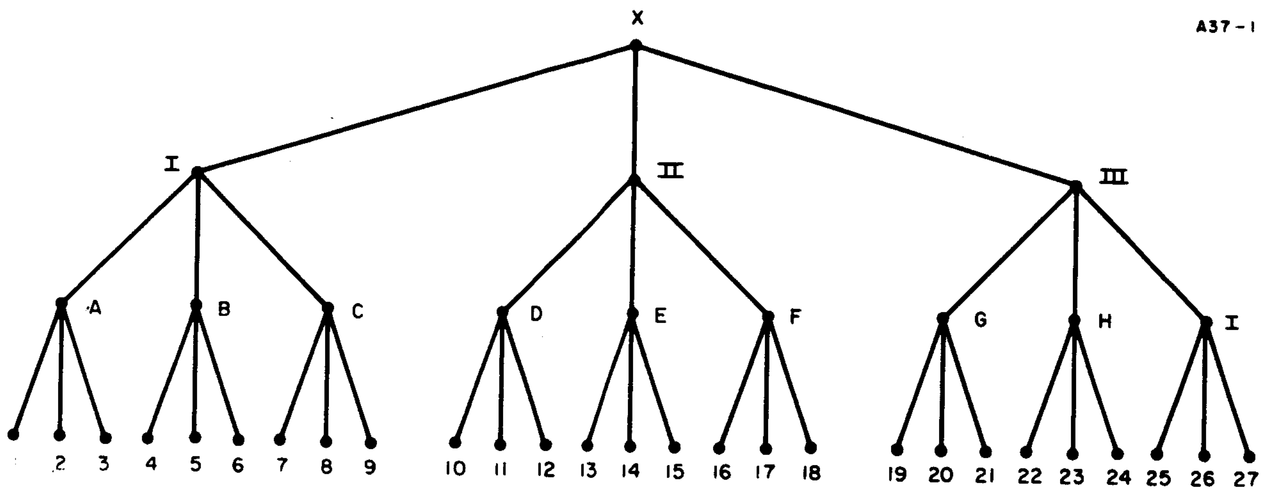

Fig. 5. "Chain of command" type interconnections.

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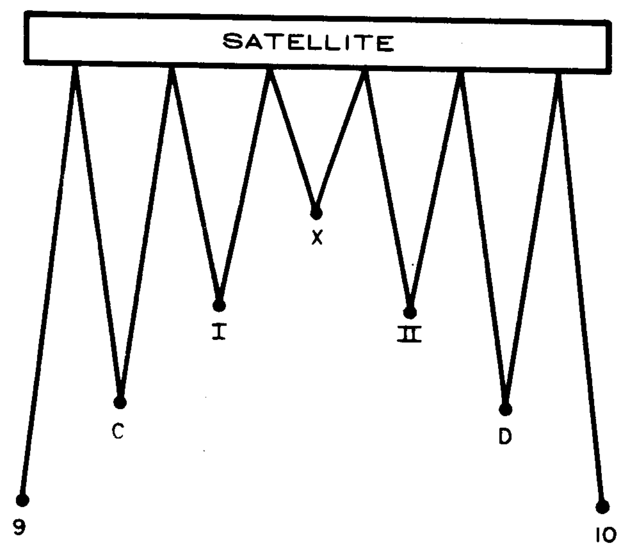

Fig. 6. Path links from Station 9 to Station 10 using "chain of command" system of Fig. 5.

D. Moving versus Stationary Orbit Systems

On purely technical grounds, stationary satellites are not essential for multiple access. Primarily economic arguments favor stationary satellites for multiple access, especially with light-load stations for which the cost of steerable tracking antennas could be prohibitive. This antenna problem, however, will also be discussed later. Since "economic arguments" may remain argumentative until resolved by competitive survival years hence, we still need to discuss the orbital aspects of multiple access on a broad technical basis.

Introductorily, one can generalize that no station can track the same satellite continuously unless its orbit is synchronous with the earth's rotation and unless the orbit's inclination and ellipticity are within certain limits. An obvious special case occurs when inclination, ellipticity and orbit perturbations are zero (or adequately corrected). A truly stationary satellite does not require tracking.

Nonsynchronous satellites must "rise" and "set" in relation to any earth station, so they can be tracked and used only for limited periods. However, communication should be continuous, or as nearly so as economics permit. Hence, earth stations need to acquire and start tracking a new and available rising satellite and, in unison, "hand-over" the circuit to it before the previously used satellite sets. This hand-over requirement imposes certain constraints or complications to the use of nonsynchronous satellites in multiple access systems, although these constraints need not always be technically prohibitive. To facilitate further discussion, however, it will be helpful first to examine and dispose of certain "global system" aspects of multiple access satellite systems in a way which will justify concentrating on one-hop systems.

E. Global Coverage Aspects

The earth coverage area, from which a satellite is visible, cannot be large enough for a truly "global" system. Even for the stationary satellite it is little more than a third of the earth's area. A usefully global system requires more satellites and requires their use in any (or all) of three ways: (1) by multi-hop circuits with intermediate earth relays (or, eventually, direct satellite-to-satellite relays); (2) by earth stations having access to more than one (first-hop) multiple access system and selecting one in the desired direction; (3) by surface communication extensions ("tails") from the terminals. The first of these is self-descriptive and generally familiar. The remaining two are illustrated by Fig. 7, which assumes stationary satellites and coverage to a 5° minimum elevation angle from earth.

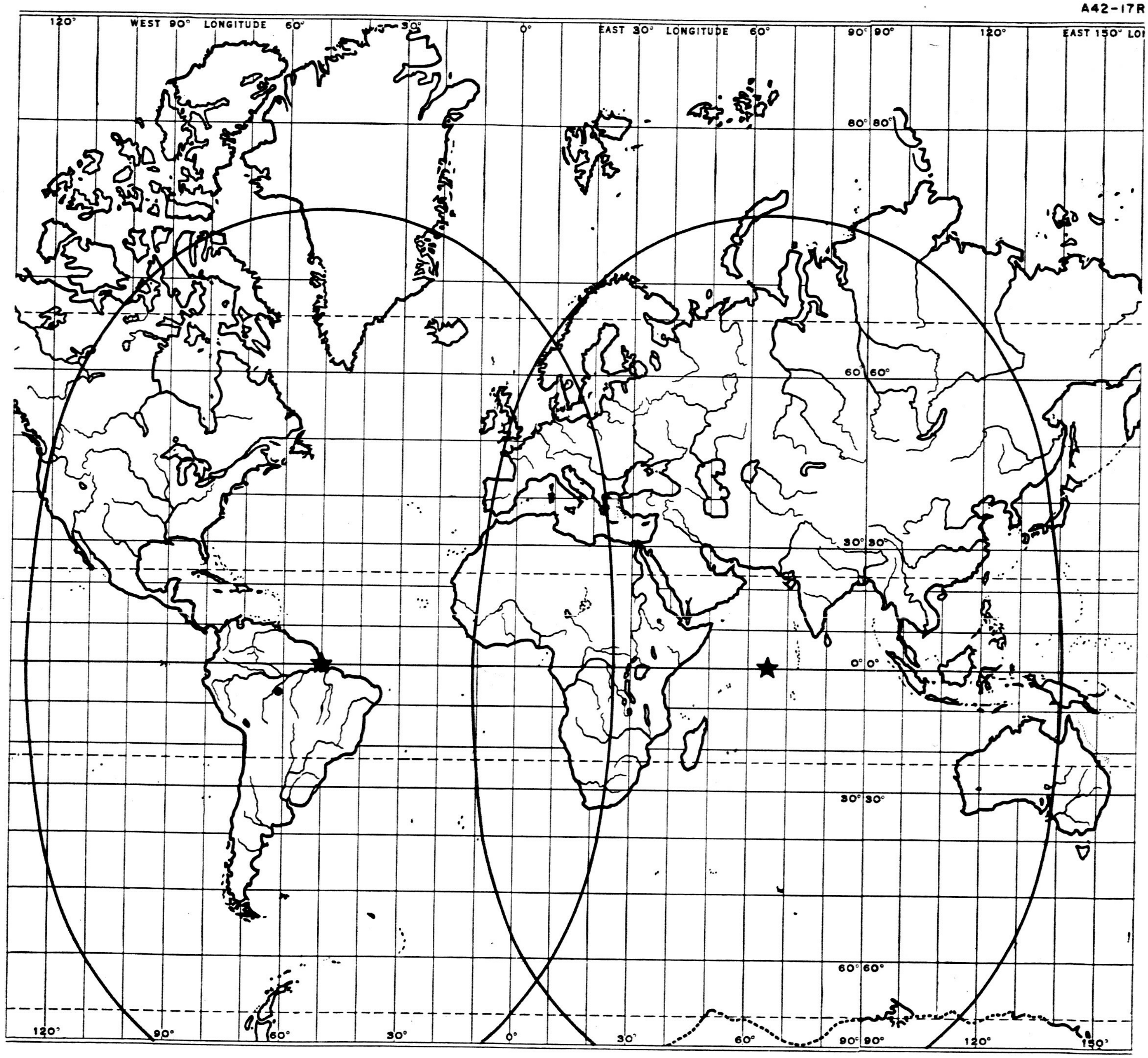

Fig. 7. Coverage areas of two stationary satellites. Satellites are placed at 50° W and 65° E. Minimum antenna elevation angle equals 5°. Note one-hop coverage from Europe to Australia and Japan.

A station near London, for example, would have its choice of working into the western satellite's multiple access complex and thus to stations nearly anywhere in the Americas, even to Vancouver. Via the eastern satellite, London would have communication to stations as far east as Australia. From there, land lines and a submarine cable could extend the communication to New Zealand, and with less propagation delay than if a second stationary satellite were used. Of course, Vancouver could have two-hop communication with Australia, relayed through the London station. However, the pause-to-reply delay would be more than a second, hence probably excessive.* Vancouver could communicate with Australia or New Zealand better via a Pacific stationary satellite's multiple access complex. Given a choice among enough stationary satellites, there would be very few important circuits which could not be one-hop circuits. Most of these few could be surface extended, as with the London-New Zealand example. Hence, multihop use of satellites need be considered only in relation to nonstationary satellite systems, having lower orbits.

In comparison with inter-satellite relaying via an earth station, direct satellite-to-satellite links offer advantages, but also problems. These problems need not be discussed beyond observing that acceptable solutions probably will complicate the satellite enough to delay application only to satellites of subsequent generations. Consequently, earth relaying will be assumed.

In most respects, one can regard a relay station as just another earth station in a one-hop multiple access system. Consequently, attention can be focused on such systems and most conclusions then can be extended readily to multihop systems.

F. Hand-Over Constraints

As previously mentioned, achieving communication continuity with nonsynchronous satellites requires periodic hand-over from the setting satellite to an available rising one. In a two-terminal system, both stations acquire and start tracking the same rising satellite, then hand-over the circuit to it simultaneously. Hence, both stations must be within the area of overlapping coverage from the two satellites at the instant of hand-over.

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*CCITT Study Group XII reported in June 1962 that it proposes to recommend, in the absence of any echo, a maximum round-trip propagation time of 700 msec. This is adequate for one-hop stationary satellite circuits but not for such two-hop circuits. Source of this information is CCIR 10th Plenary Assembly (Geneva) Doc. 20, for S. G. IV, dated 27 July 1962, a note by the Director, CCIR.

With a one-hop multiple access system of N stations, achieving simultaneous hand-over requires that all N stations be within the area of overlapping coverage. To clarify this, Fig. 8 shows four stations which have been communicating via satellite 1 which is setting. Stations A, B, and C are also within the coverage area of a rising satellite, 2, so they start tracking it with a second set of steerable antennas, preparatory to hand-over. Station D could have communication with the other three stations up until this instant but could not start tracking and using the second satellite until some later time at which it comes within its circle of coverage.

Such an interruption might or might not be tolerably brief.

With a random orbit system the area of overlapping coverage will differ somewhat for successive hand-overs, being large when the two satellites are close together and becoming small, or occasionally becoming nonexistent, if the two satellites are far apart. Moreover, the shape or orientation of the overlap area at hand-over may change, depending upon whether the hand-over is to a satellite in the same orbit plane or in an adjacent orbit plane. Consequently, it appears that the earth area of one-hop multiple access system operation using random-orbit satellites would be a function of the required probability of uninterrupted service, somewhat as indicated in Fig. 9, with this probability deteriorating as the system's area is increased. The use of random-orbit satellites does not necessarily preclude one-hop multiple access operation but such operation seems less reliable, hence, less attractive, than with a system of accurately phased equatorial orbit satellites. For such a phased system there can be uninterrupted operation between all stations in a well-defined area.

The stationary satellite is considered best for one-hop multiple access because its entire coverage can be used, without hand-over constraints and additional antenna costs.

The coverage overlap from two stationary satellites is of some interest, however, because those stations within their overlap area can have access to either or both satellites, as was discussed in connection with Fig. 8.

The coverage overlap areas for satellites of various equal heights and given separations has been studied in a companion report, ref. 2. Table II from this reference shows adjacent satellite overlap areas for

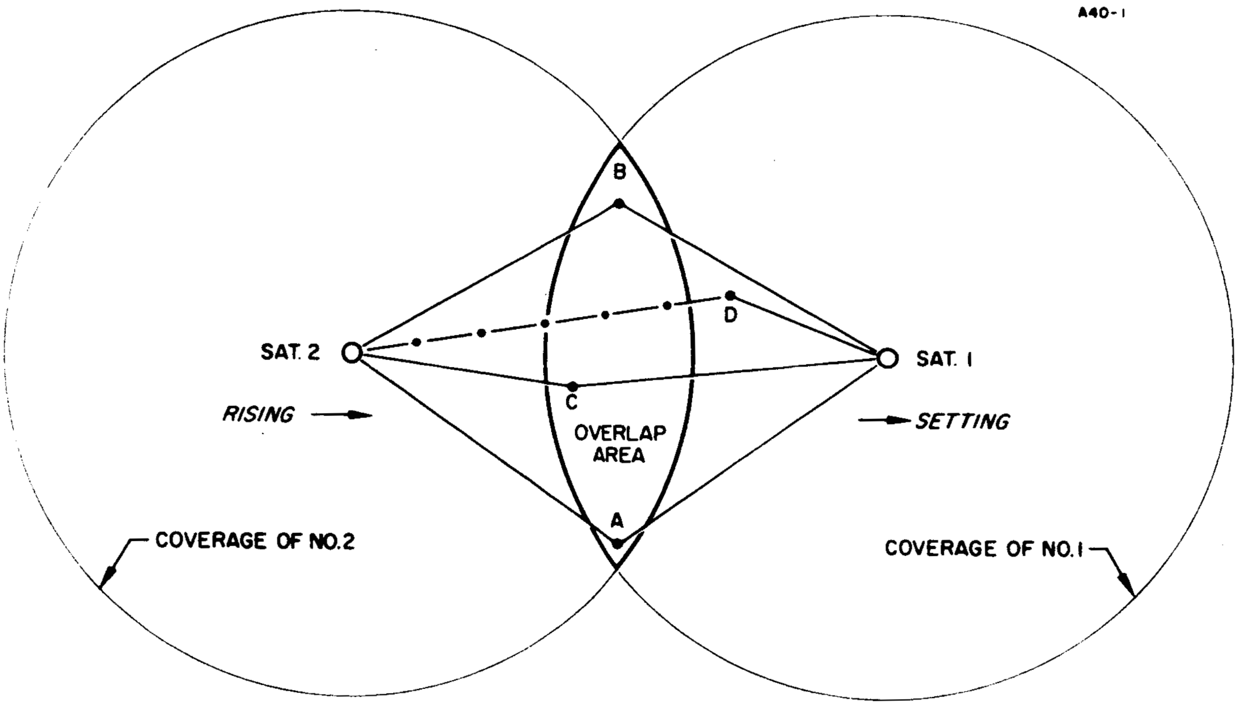

Fig. 8. Coverage overlap of two nonstationary satellites.

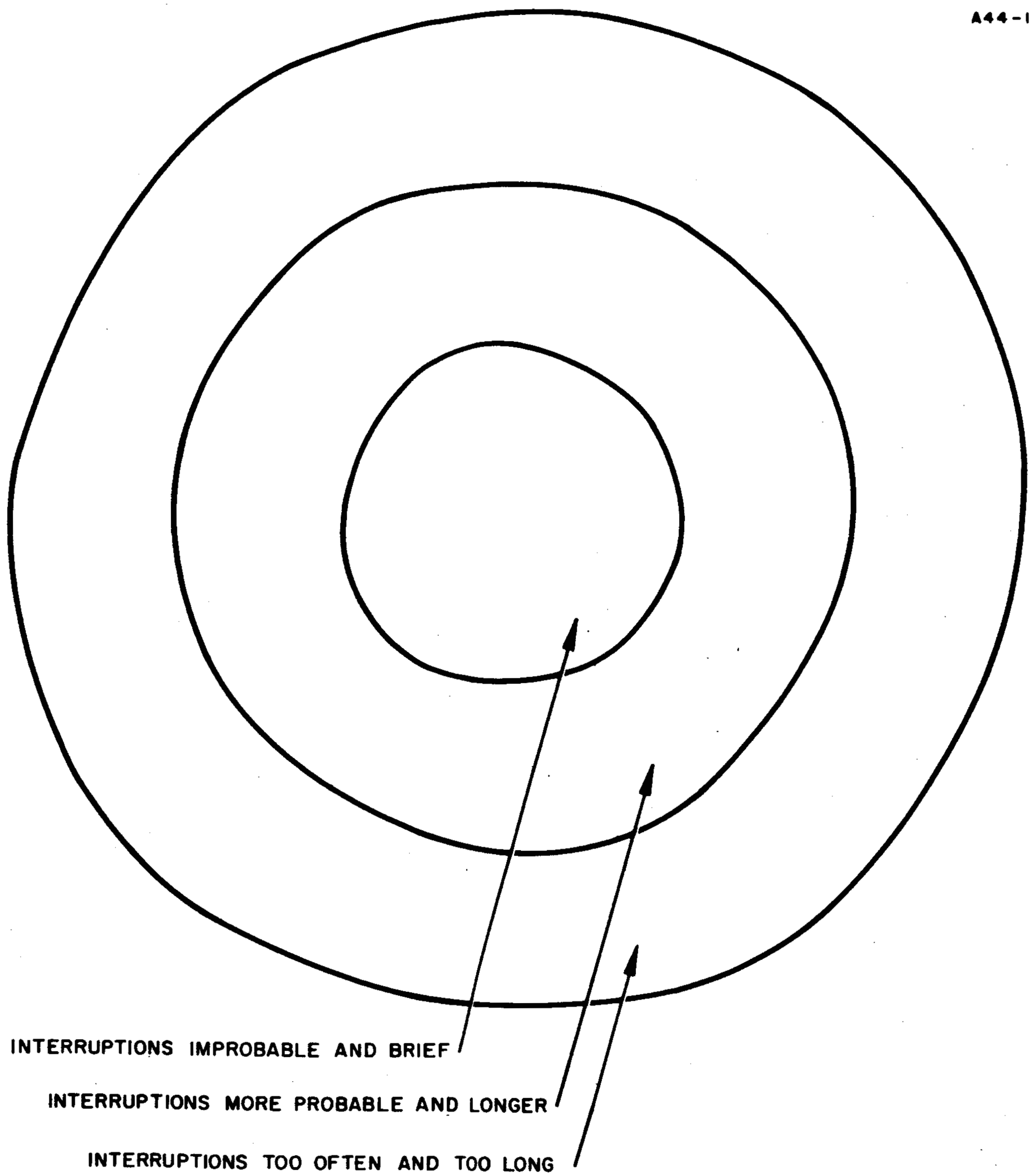

Fig. 9. One-hop multiple access system area, with random-orbit satellites, is related to the severity of hand-over interruptions.

various numbers of satellites equally separated around a circular orbit of specified height, the areas being expressed as percent of the coverage area of a stationary satellite. Values are given for both zero and 10° minimum elevations above the horizon. Clearly, too few satellites around too low an orbit lead to too little overlap. However, useful areas definitely are obtainable. Figure 10 illustrates this more vividly than the Table by showing the coverage overlap of the Atlantic Basin obtainable with 12 satellites, 30° apart around a 14,000 km equatorial orbit, assuming 5° minimum elevation. One could have four-continent multiple access via this orbit system. Reference to Fig. 7, however, shows the larger area obtainable from one stationary satellite.

III. MODULATION AND MULTIPLEXING ASPECTS OF MULTIPLE ACCESS

This section will discuss some of the factors which may influence the choice of modulation and multiplexing methods for multiple access satellite systems. One-hop systems will be considered for illustration.

The basic requirement is to combine (multiplex) the earth station transmissions at the satellite receiver, then let the satellite retransmit this combination in a suitable manner such that each station can receive and select its desired signals from those to other stations. This is a somewhat unique requirement in radio communication. With microwave links, for example, all of the multiplexing can be done at the terminals. Multiplexing the signals from many distant transmitters may require good system coordination.

The multiplexing at the satellite receiver may be achieved via (1) frequency division, (2) time division, or (3) common-spectrum ("orthogonal modulation") techniques. To a degree at least, the satellite receiver multiplexing can be discussed independently of the voice-channel multiplexing and modulation used by the earth stations. Figure 3 illustrated frequency division multiplexing at the satellite in a permanent channel multiple access system. Presumably, the sub-bands to the various earth receivers would have their voice channels frequency division multiplexed also, but not necessarily. Each could be a time division multiplex of pulse code modulated (PCM) voice channels, provided that it were held within allocated bandwidths of these sub-bands.

The choice of multiplexing and modulation techniques may also be heavily influenced by the intended application. For example, digital signaling, even for telephony, may well be a requirement for military satellite systems to achieve compatibility with communication security systems. Analog signaling (FM, SSB, etc.) probably will remain preferred in common-carrier satellite systems for different compatibility and economic reasons.

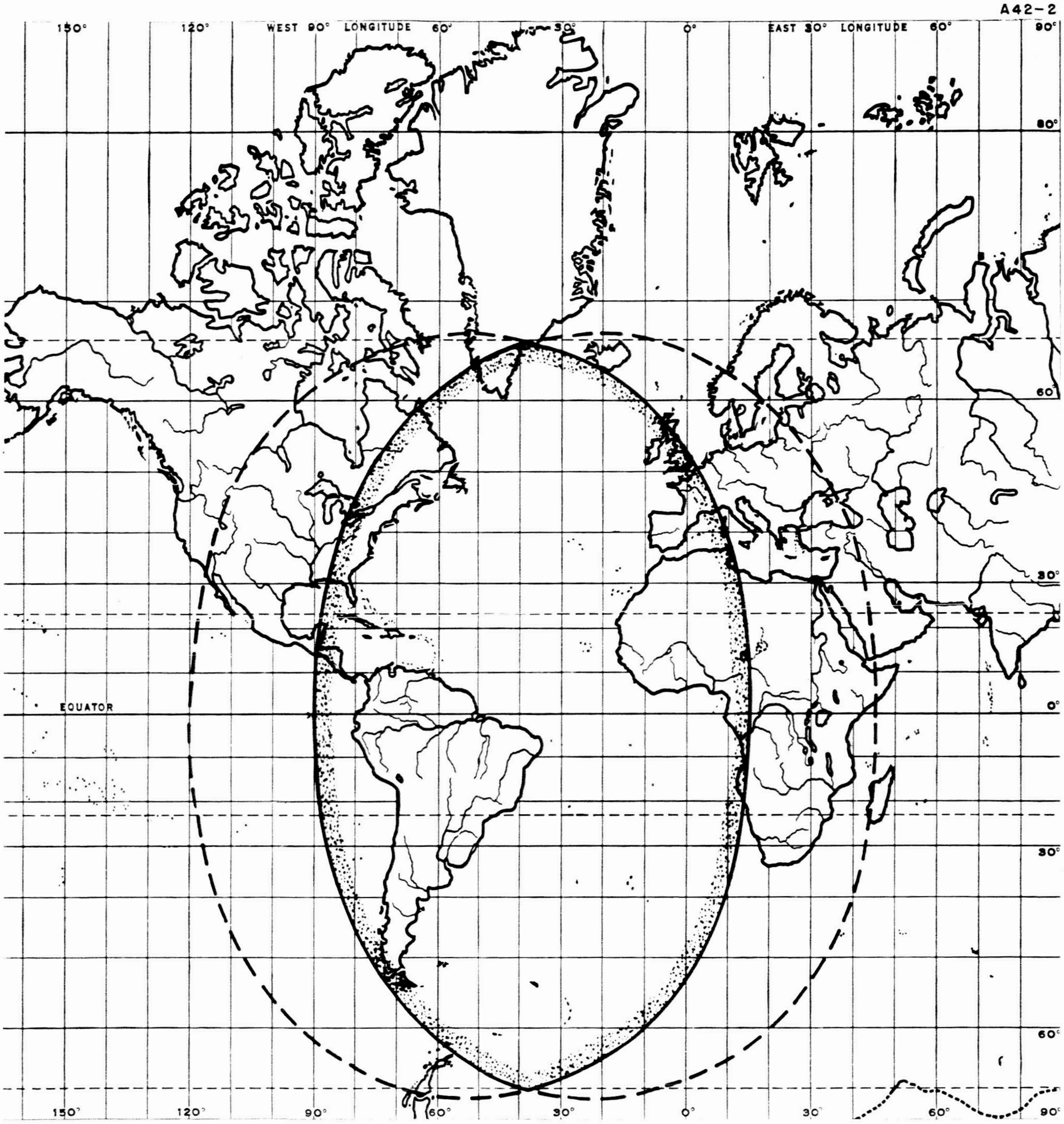

Fig. 10. Coverage overlap area over Atlantic Basin with U. K. System. Satellites are in phased orbit of 14,000 km height, separated 30° and with a minimum elevation angle of 5°.

Another complication which has plagued choices or discussions of "preferred" modulation for satellite communication is the difference between what we can do (or are doing) today and what we should (and can) do sometime in the future. Today's satellites have limited transmitter power, but ample spectrum bandwidth is available, so we use wide FM with feedback reception on earth to help compensate for the satellite's low power by trading bandwidth for improvement of the signal-to-noise ratio. Then, in a two-terminal system such as Fig. 1, having no multiplexing requirement at the satellite receiver, we probably transmit the same wide FM to the satellite, letting it be a simple frequency translating repeater. Ample power is available to earth transmitters, however, so other modulation could be used from earth to satellite. Sometime in the perhaps not too distant future, the demand for satellite communication will grow to require 6000 channel satellites, rather than 600 channel ones, but with no increase in the then-allocated channel bandwidths. At this time the satellite power will be increased and modulations less wasteful of the spectrum will be used. The conclusion is that planning and development toward multiple access satellite systems should not be needlessly restricted to, or confused by, today's state of the art.

A. "Common Spectrum" Multiplexing for Multiple Access

Returning to the consideration of multiplexing of the earth transmission at the satellite receiver, the common spectrum techniques are newer and less generally familiar than the frequency division and time division techniques, so they require examination and discussion. The discussion will lead to the conclusion that the common spectrum techniques command understandably strong military interest but that, thus far, their cost (complexity), inefficiency of spectrum utilization, and other limitations have not made them attractive for common-carrier satellite systems.

Common spectrum multiplexing seems to have had its birth in spread-spectrum anti-jamming technology, in which signals are so "coded" or manipulated as to achieve a multiplicity of correlative characteristics and (or in exchange for) a corresponding increase in bandwidth. Such signals can be recovered through heavy jamming or other noise by suitable correlation detection or similar techniques.

Suppose now, for example, that a signal is so coded and spread in its bandwidth that it is noise-like and can be recovered and read through noise jamming which is 20 dB (100 x) stronger. It would be immaterial whether this noise-like interference resulted from one jammer or from 100 other spread-spectrum communication transmitters of which the total power equals that of the jammer. Each such signal, having a code "orthogonal" to all the others, could be received and read independently, though all shared a common spectrum and seemed hopelessly superimposed in both frequency and time.

Illustratively, a matched filter such as a suitably tapped delay line may be used for the correlation detection. Full correlation (maximum output) will be obtained if the time-frequency characteristics of the receiver are those which the delay line filter matches. Essentially, no output would be obtained if the signal were completely uncorrelated with the characteristics of the filter. However, a signal matched to this filter could be submerged in a noise-like background of differently coded signals and still retain enough correlative characteristics to be extracted usefully by the correlation detection process.

The above discussion of tapped delay lines, correlation, spectrum-spreading, coding, etc., has been kept nonmathematical and hence may not seem usefully clear and specific. If so, an admittedly "antique" and over-simplified example may help.* Consider a binary digital transmission system such that 1's are received as positive pulses and 0's as negative pulses. For the "marks" and "spaces" of teletype characters, we code spaces with the Barker (self-correlating) binary sequence, 1011000 (i.e., a +-++--- pulse sequence) and marks by the 0100111 sequence. In doing this, we transmit seven pulses for each teletype pulse (mark or space) so we spread the signal's spectrum by seven fold.

At the receiver this pulse train enters a delay line having seven taps, each separated by a delay of one pulse period. All taps feed into an adder, but only after the outputs from three taps have been passed through polarity reversers as shown in Fig. 11. When the coded train of seven pulses reaches the end of the line, each pulse position coincides with a delay line tap, as shown. If the pulse train is that for a mark, the three zeros (negative pulses) are reversed, so seven positive pulses enter the adder. Similarly, for a space, the three ones are reversed and seven negative pulses enter the adder. At any other time except when either of these pulse trains are in coincidence with all seven taps, the adder output will not exceed that from one positive or negative pulse, as the reader may easily verify as an exercise. Moreover, and perhaps more important, no other binary sequence of seven pulses than these two can produce the full $\pm$ outputs from the adder. However, one may reverse several pulses in these trains (as if the result of interference) and still obtain unmistakably large + or - outputs from the adder as a consequence of the remaining partial correlation. Fig. 12 is a "do it yourself" aid for further clarification of this self-correlating code.

Such a relatively simple system as this obviously would be inadequate for a common-spectrum multiple access system. For one with, say, a hundred-fold its capability, we should perhaps envision one with

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*This example is derived from the "LONG ARM" system of HF communication, vintage of about 1954.

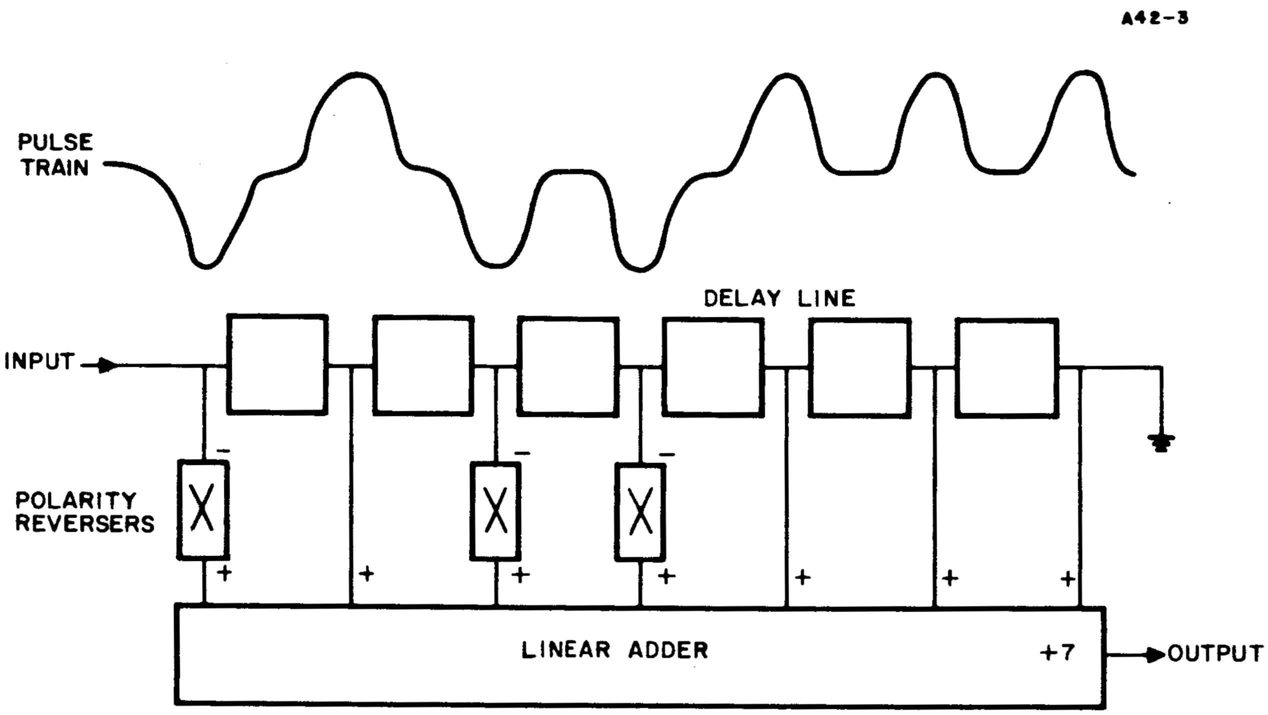

Fig. 11. Tapped delay line filter for 7-bit Barker code.

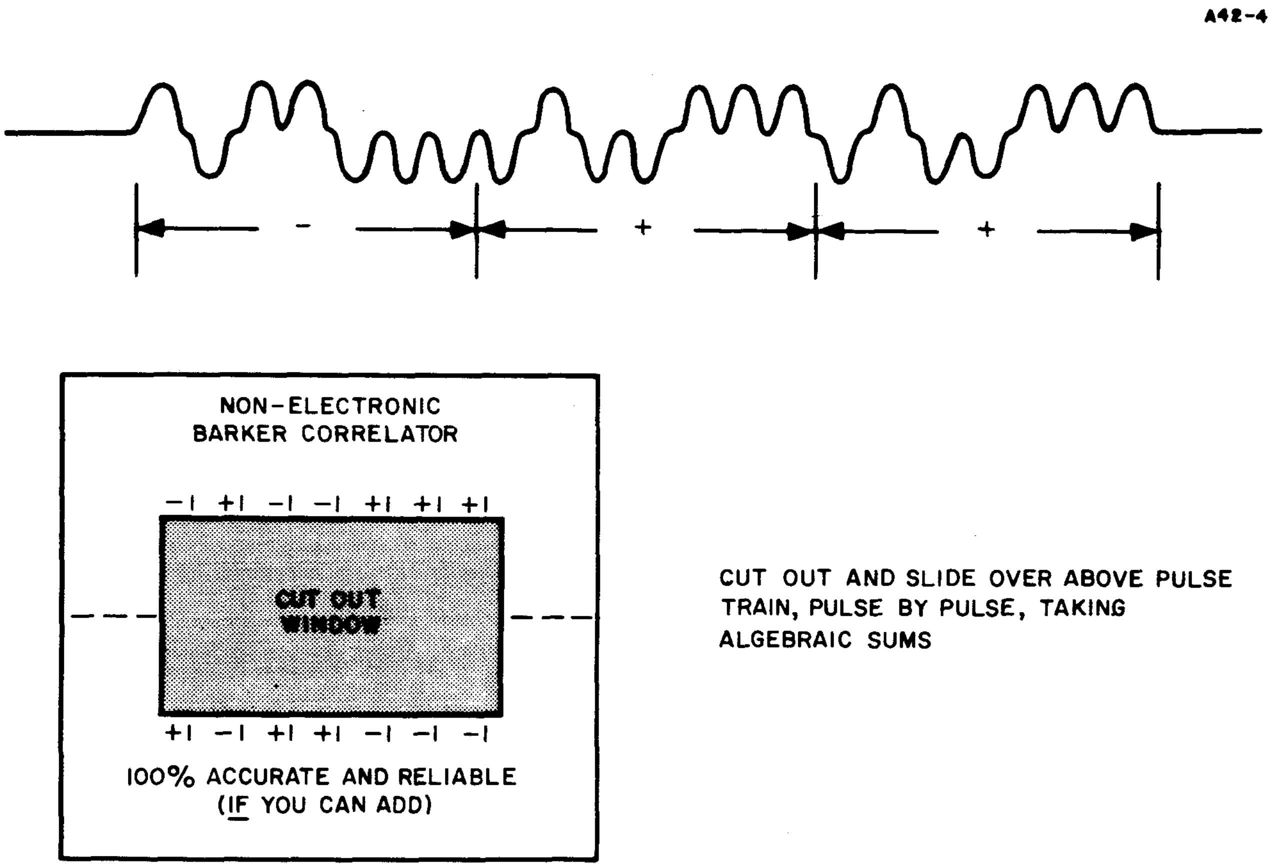

Fig. 12. "Do it yourself" teaching aid. Applies to 7-bit self correcting Barker code. Cut out figure as indicated and slide over the pulse train in step-wise fashion over each pulse taking the algebraic sum at each step.

hundred-fold complexity of its signal coding and consequently also of its correlation detection system. Thus, one begins to understand why common-spectrum multiplexing appears economically unattractive, thus far at least!

A much deeper penetration into common-spectrum multiplexing technology might well lead into too thorny a thicket of proprietary and security obstacles, but a few generalizations will be made, without giving adequate supporting reasons.

The contemplated signal inputs for such systems generally are digital. Hence for PCM voice, the input baseband might be 50 kc, for example. If spread a thousand-fold by the coding, the coded bandwidth would be 50 Mc, the probable width of a satellite channel. The coding can be analog (a noise-like waveform) or digital (a time-frequency pulse pattern). Synchronization may be required and may be difficult to achieve. Synchronization obviously is undesirable but most attempts to avoid it seem to result in loss of system capacity, much as if synchronization itself had information content! Practical systems have a threshold limitation which results in not obtaining a channel capacity greater than, say, 10% of the spectrum spreading ratio. Thus, for the above PCM example, one might be able to multiplex (superimpose) only 100 such channels, despite the 1000 x spreading ratio.

A frustratingly great attractiveness of these techniques is their potential simplification of "calling." One needs no auxiliary order circuits, calling codes, or master control; one need merely start sending with the code which matches the desired receiver's filter! With this "wouldn't it be nice if —" observation, we proceed to the more mundane but commercially useful techniques, while still praying for a breakthrough in the simplification and improvement of common-spectrum technology.

IV. STATION VERSUS SATELLITE MULTIPLEXING FOR RANDOM MULTIPLE ACCESS

It was stated earlier that, to a degree, the satellite receiver multiplexing could be discussed independently of the voice-channel multiplexing and modulation used by the earth stations. Actually, there are practical or economic restrictions on these two forms of multiplexing and they become important in relation to random multiple access systems for reasons discussed in this section.

Figure 13 is a conceptual diagram of such a system and is intended to emphasize that each station should have access to <u>any</u> of the satellite's circuits as needed. In this instance each station has available

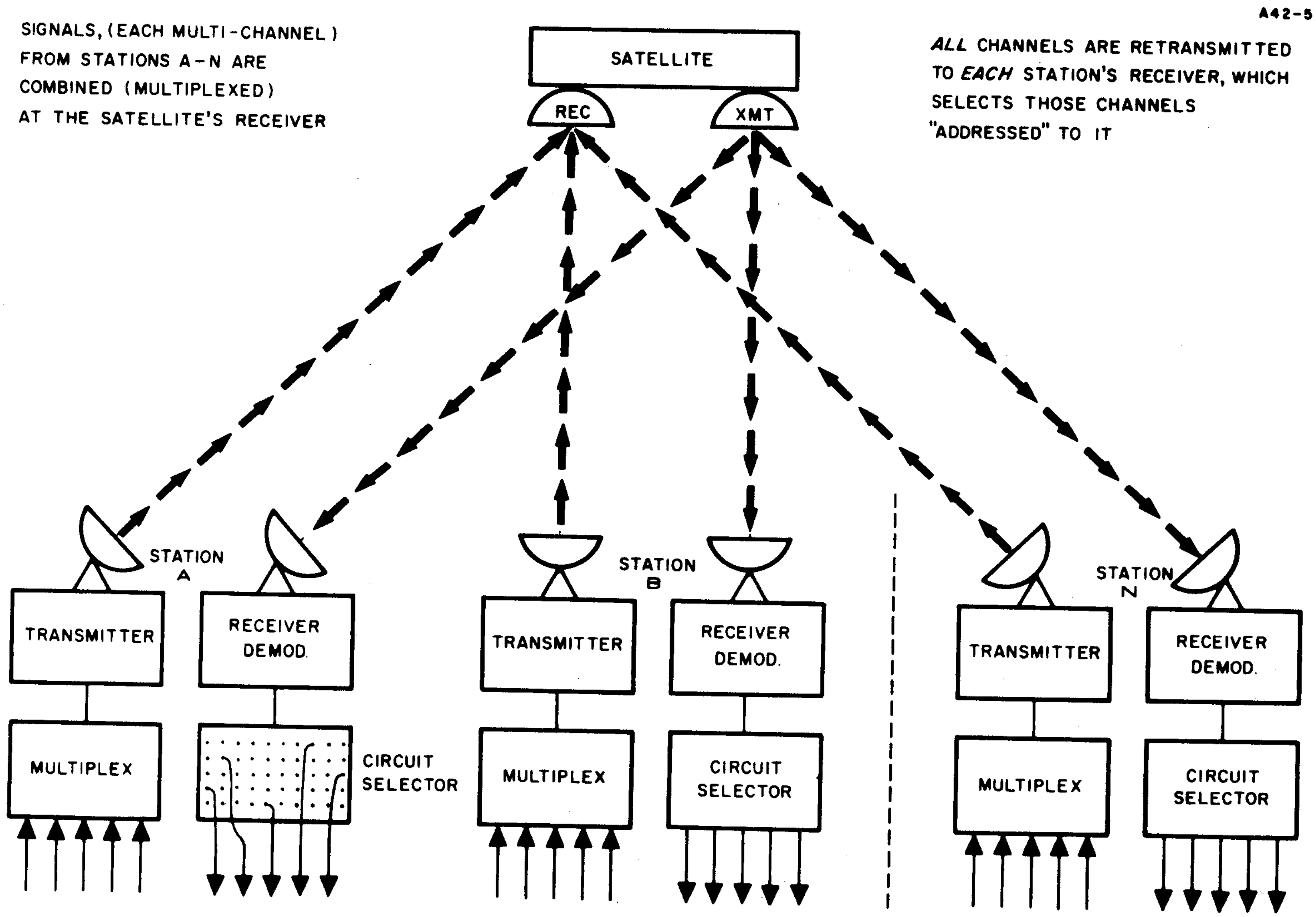

Fig. 13. Conceptual diagram of a random multiple access system.

all voice (or other) circuits from the satellite from which it can select those few which it uses at any one time. It has a corresponding few transmitting circuits to the satellite which are assigned to it, somehow, by the "system." The obvious alternative would be to assign the required number of receiving circuits to each station and to make all transmitting circuits available to each station. The choice between transmitting and receiving circuit assignment methods involves the auxiliary calling and system control subsystem and such practical matters as relative ease and cost of circuit selection at the transmitter or receiver. Receiver selection seems preferable, at least when frequency division multiplexing is used, because of the power level. It is generally easier and less costly to do any switching or channel selection at the lowest possible power level. Receiver selection will be assumed henceforth, although it should be recognized that considerations not now anticipated could favor transmitting circuit selection.

In Fig. 13, station A's receiving circuit selector is shown as if it were a switchboard into which an operator could insert plugs into circuit jacks 1-50. Assume also that A is assigned transmitting circuits 1-5, B circuits 6-10 and N circuits 46-50.

Assume also that all station operators are in communication over an auxiliary order circuit. Their problems will be discussed in a subsequent section. If A has a party wishing to talk to a party in the vicinity of B, A's operator connects to an idle transmitting circuit, say No. 2, and tells B to select circuit 2. B does, and decides to put the reply on circuit 7, so B says, "B back to A on 7." A selects circuit 7 for its party and their call proceeds until completed, whereupon the circuits are released.

If A has been allocated five transmitting circuits, as shown, it could process calls with four other stations during this call with B, or even process all five calls with B if necessary. All other stations would have similar freedom of interconnectability.

Note that thus far, nothing has been said about frequency division, time division, or other multiplexing. Conceptually, the satellite could be just a junction box entered by five-circuit cables from transmitters of each of, say, ten stations, and having 50-circuit cables to each station's receiver. The transmitting circuit variant of this would have 50-circuit cables from each transmitter and five-circuit cables to each receiver. In comparison, a "permanent channel" system of ten stations would need nine (one-way) circuit cables from each station, through the satellite, one to each of the other stations; a total of 90 circuits for not more than one conversation at a time between any pair of stations.

Instead of cables, we use multiplexing to separate radio circuits, and multiplexing is somewhat interrelated with the types of modulation employed. For simplicity of illustration, we will consider only three of the many possible types of modulation; (1) single sideband (SSB), (2) frequency modulation (FM), and (3) pulse code modulation (PCM). Respectively, these typify conveyance of information by changes in (1) amplitude, (2) frequency, and (3) time. Additionally, we consider only frequency and time division multiplexing and the possibility of a modulation change in the satellite, such as from SSB to FM. Table I shows the possible combinations and permutations of these techniques for the earth/satellite system, a total of 36. Many of these are illogical, even to being difficult to conceive of. For example, case 36 clearly is illogical because the satellite receives a full time-division multiplex of pulse code modulated circuits. One certainly would not perform additional pulse code modulation on a PCM signal. It would be logical not to remodulate such a multiplex in the satellite (case 34) and perhaps conceivable to frequency modulate this multiplex for transmission to earth (case 35). The other 11 cases which propose changing to PCM in the satellite appear beyond the state of the art, if not illogical, because of excessive sampling rates and coding difficulties in a light and reliable (simple) payload. Were it not for these problems, the change to PCM might be considered as another "logical" way of trading bandwidth for S/N improvement to compensate for limited satellite power. Changing to PCM in the satellite, however, would not satisfy certain requirements for all-digital communication. Frequency modulating the satellite's transmission is a simpler way of trading bandwidth for S/N improvement, when necessary. It would appear illogical to frequency modulate in the satellite if it receives a frequency modulated signal; however, one might use narrow FM as the initial channel modulation in lieu of SSB, then FD multiplex in the station transmitters and at the satellite receiver, and finally retransmit with wide-deviation FM (case 14) to obtain S/N improvement.

Table I is incomplete in that it neglects possible remodulation of the channel groups by each station transmitter. For example, an FD multiplex of SSB channels could be frequency modulated (or pulse coded) as a group for transmission to the satellite. Inclusion of the three group modulation possibilities would, however, increase the number of cases to 108, adding further confusion. In general, mixing modulations of channels, groups, and satellite is undesirable in that it may complicate the station receivers' channel selection to an uneconomic degree. For example, if each station frequency modulates its group of frequency multiplexed SSB channels, with further FD multiplexing at a satellite's straight-through repeater, each earth receiver would need to separate these groups by their frequency bands, pass each through an FM detector, then finally select the desired few SSB channels. This reasoning is, of course, independent of other arguments against use of frequency division multiplexing after frequency modulation of channels or groups.

TABLE I

	Channel modulation	Channel (station) multiplexing	Satellite (group) multiplexing	Satellite to earth modulation
1	SSB	FD	FD	SAME
2	SSB	FD	FD	FM
3	SSB	FD	FD	PCM
4	SSB	FD	TD	SAME
5	SSB	FD	TD	FM
6	SSB	FD	TD	PCM
7	SSB	TD	FD	SAME
8	SSB	TD	FD	FM
9	SSB	TD	FD	PCM
10	SSB	TD	TD	SAME
11	SSB	TD	TD	FM
12	SSB	TD	TD	PCM
13	FM	FD	FD	S
14	FM	FD	FD	FM
15	FM	FD	FD	PCM
16	FM	FD	TD	S
17	FM	FD	TD	FM
18	FM	FD	TD	PCM
19	FM	TD	FD	S
20	FM	TD	FD	FM
21	FM	TD	FD	PCM
22	FM	TD	TD	S
23	FM	TD	TD	FM
24	FM	TD	TD	PCM
25	PCM	FD	FD	SAME
26	PCM	FD	FD	FM
27	PCM	FD	FD	PCM
28	PCM	FD	TD	S
29	PCM	FD	TD	FM
30	PCM	FD	TD	PCM
31	PCM	TD	FD	S
32	PCM	TD	FD	FM
33	PCM	TD	FD	PCM
34	PCM	TD	TD	SAME
35	PCM	TD	TD	FM
36	PCM	TD	TD	PCM

Note: The additional possibility of group modulation at each transmitter has been omitted in interests of simplicity. Its inclusion would lead to 108 cases.

Best utilization of the spectrum would be obtained with case 1 in Table I (SSB, FD, FD from satellite) in that the bandwidth to and from the satellite would be just the baseband (i.e., total bandwidth of all circuits) increased as necessary by guard bands. One of several present objections to such an all-SSB-FD system is that it would require a relatively powerful satellite transmitter for acceptable signals (high S/N) to the earth receivers. Hence, case 2 helps by frequency modulating the satellite's transmission so that, with feedback FM detection at the earth stations, acceptable signals can be obtained from present low power satellites. Only one feedback FM detector is required at each earth station, after which there can be direct frequency selection of the desired SSB channels. Hence, this approach leads to relatively simple and inexpensive earth transmitters and receivers. Additionally, the satellite can be relatively simple with little additional circuitry being required to introduce the wide deviation FM or PM (phase modulation).

The use of "compandors" (transmitting volume compressors and receiving volume expanders) is frequently proposed as a means of S/N improvement and of reducing the transmitter peak power requirements of SSB systems. The amount of improvement thus obtainable is uncertain but it should be substantial. Compandors are "arty," however, in relation to speech degradation and user acceptance. The so-called instantaneous compandors introduce distortion frequency components when the bandwidth is held constant, whereas the slower syllabic compandors may not fully compress the initial speech sounds, thus making them seem to "bark." Compandors seem to deserve further investigation.

Recognizing that this study has not yet explored other practical problems of such a system, nor considered the many other types or variants of amplitude, frequency (or phase) and time modulation, it would seem controversial to call this SSB-up-FM-down (case 2 in Table I) system the "preferred" system. One observes, however, that it has become "preferred" by at least three leading U. S. companies for nonmilitary (i.e., nondigital) satellite communication. Unless developmental problems become unforeseeably difficult and can be avoided by changing to some yet-unidentified or even yet-uninvented "dark horse" system, SSB-up-FM-down may well become the universally preferred means of obtaining random multiple access in common-carrier systems. Adequate discussion of such possible problems and their possible cures is beyond the scope of this introductory study.

For two-terminal satellite systems (i.e., no multiple access), certain of the preceding arguments vanish. An FM-up-FM-down system with a straight-through satellite repeater becomes simpler, hence preferable, even though earth transmitter power is ample and FM improvement of S/N from earth to satellite is not needed.

Suggesting a preferred random multiple access modulation and multiplexing system for military systems could be more controversial, if only because of uncertain military requirements. One relatively certain requirement, previously mentioned, is that all (or most) signals be digital. If so, one observes that an all time-division system could become the analog of the all frequency-division system (SSB up and down) in regard to its relative efficient use of the spectrum. After once accepting the bandwidth penalty of PCM voice circuits (about 10 x), there need be but negligible further penalty (i.e., comparable to the guard band penalty with FD) from exclusive use of TD multiplexing. The synchronizing and delay problems are not necessarily insurmountable, as some have claimed. One can compensate for anticipated delays and delay differences. Only the residual and relatively random unanticipated delay differences measured as a few nanoseconds determine the guard-slot time losses. This observation does not imply that an exclusively time-division system will become the preferred military system. Simplicity and efficient use of the spectrum may be requirements of relatively low priority.

Further discussion and mathematical comparisons of the relative advantages of various modulation methods suitable for multiple access systems will be contained in a forthcoming companion report, ref. 3. Additionally, the literature contains many comparative analyses of modulation methods, some of which are confusingly biased toward preconceived conclusions (see refs. 4-9).

V. RANDOM ACCESS WITH MULTIPLE REPEATERS AND MULTIPLE SATELLITES

Future satellites may use several repeaters rather than a single very broad band repeater. Feasibility studies are being made of a stationary satellite using four repeaters to improve flexibility and reliability, perhaps more than to increase its capacity for random multiple access traffic. Initially, perhaps only one repeater might be needed for this type of traffic, with the others used for point-to-point traffic, television and/or as spares. Someday, however, the random multiple access traffic demand may exceed the capacity of a single repeater.

In relation to random multiple access, the generalized use of multiple repeater satellites raises some interesting problems which we should examine. Similar problems may arise from adding stationary satellites to a one-hop random access system to increase its traffic capacity, as will be discussed later.

Let us consider a future very wide band satellite which is channelized among N repeaters. Some of these repeater channel groups will be used for heavy paired-terminal "trunk" traffic, some for television and some will be spares, but the remaining M channel groups are to be used for random multiple access. Fig. 14 shows the simplest form of such a system with M = 4. Each station, large or small, is assigned its transmitting channels in just one of these four repeater channel groups. As a consequence, with this system, each station must have four receivers but these could use the same antenna. None the less, this would increase receiver costs and complicate the use of the channel selectors.

Figure 15 shows the use of a somewhat more complex four-repeater satellite with interconnection "trunks" (at baseband) connecting certain of the receiving voice channels to each of its four transmitters. Only two of many ground stations are shown. Each earth station then could transmit and receive via the same repeater channel. For example, if X is a channel-2 (or band 2-3) station desiring to communicate with Y, a channel-4 (or band 4-5) station, X would transmit on one of the voice channels which is "trunked" in the satellite to the channel-4 transmitter and Y would tune a selector to the designated voice channel. Y then would reply in a similar manner, as indicated. An obvious potential trouble is that any one, or several, of these sixteen internal pairs of trunks in the satellite could become saturated. If these trunks are made too large, to reduce the probability of such saturation, it would invite saturation of those remaining circuits needed for communication with same-channel stations. Eventually, when satellites become reliable enough to risk sophistication, adaptive control may be applied to the channel capacities of these internal trunks. It would be simpler, however, at least from a random access viewpoint, to use a single repeater having correspondingly greater channel capacity.

As to the multiple satellite case, it is frequently claimed that a random-orbit system or a station-keeping system would make more efficient use of the spectrum than a global system of three stationary satellites, all systems having the same channel capacity. A first answer to this claim is that the stationary system probably would use SSB, initially for just the up path, but eventually for both up and down paths. With nonstationary satellites SSB is much less attractive, because of Doppler corrections, etc. Hence, for a given satellite channel width, each stationary satellite could carry many more circuits (eventually, given adequate satellite power) than the less efficiently modulated nonstationary satellite. The second answer is that, even if the same modulation were used, one could use a dozen stationary satellites as well as a dozen station-keeping satellites, or fifty random-orbit satellites used by a dozen paris of stations. If one insists on perpetuating Arthur Clarke's three-satellite concept, the

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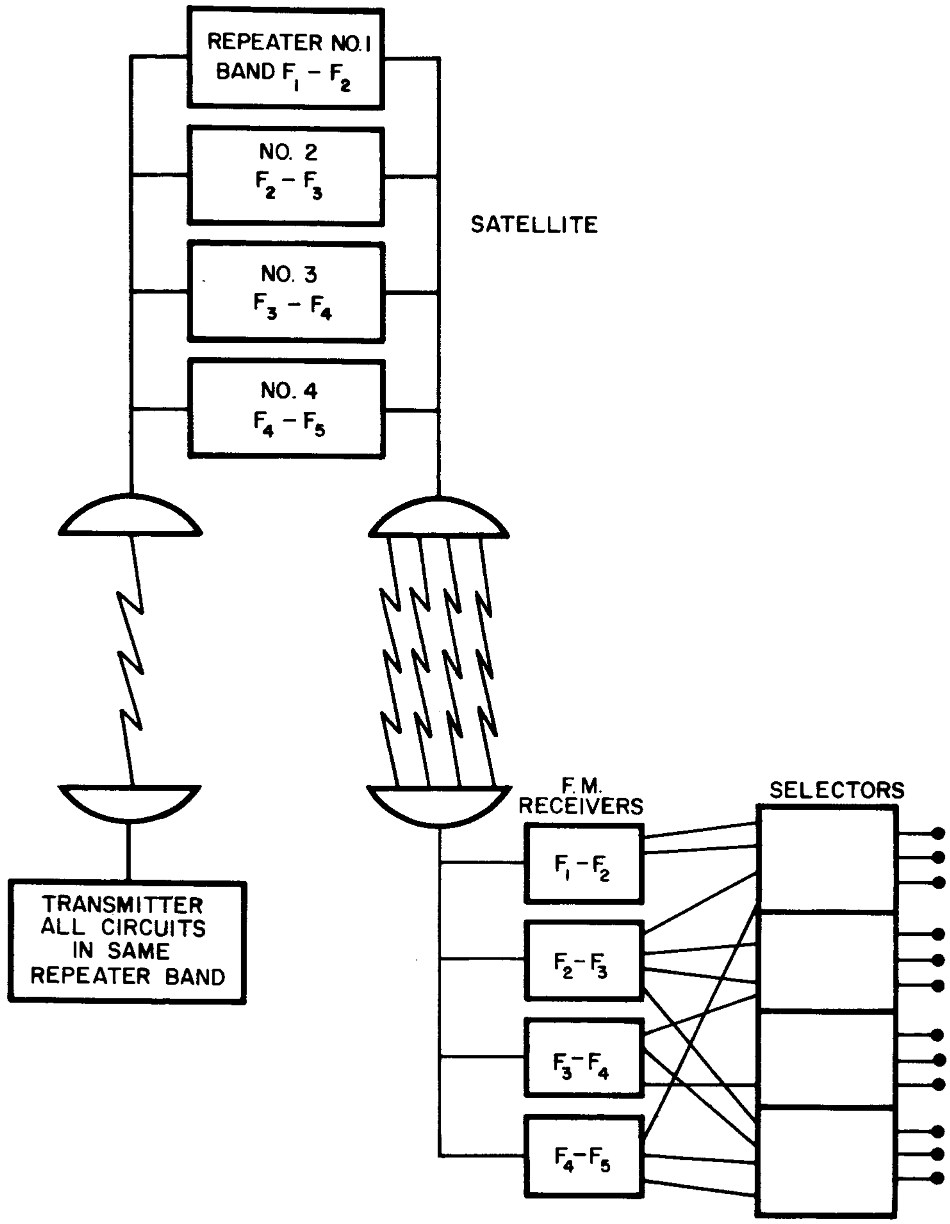

Fig. 14. Random access operation with a 4-repeater satellite.

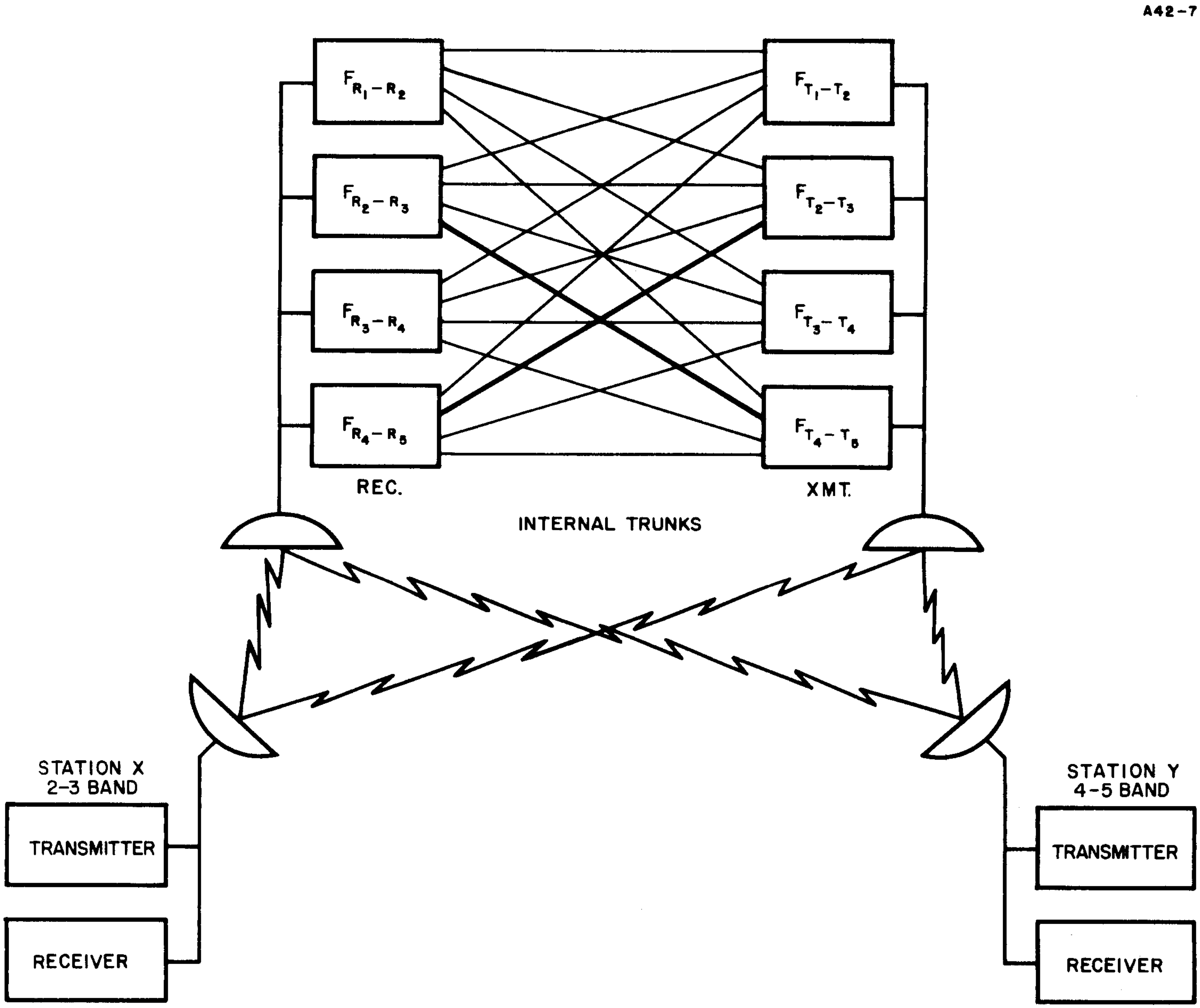

Fig. 15. 4-repeater satellite with internal trunks for same-band operation.

satellites could be clustered in fours, separated about five degrees, as shown in Fig. 16. More likely they would be located to best meet the world's needs. However, the random access problems can best be discussed in relation to a cluster of satellites being used to increase the system's circuit capacity. Figure 17 shows that a four-satellite cluster, without inter-satellite relaying, is similar to the four-repeater satellite case, previously discussed, except that each station would need four antennas. The seriousness of this would, of course, depend on how much the cost of fixed-reflector antennas can be reduced. This solution would always be objectionable for small stations, however, because antennas are fixed-cost (i.e., not "per-circuit") items. The next step would be to provide inter-satellite "trunks," as in Fig. 18.

VI. CALLING METHODS AND PROBLEMS

In land telephony one "calls" (dial pulses and ringing signals) over the communication circuits, partly because each connectable link of such circuits terminates "intelligently," to a human operator or to her automatized replacement. With manual switchboards, "drops" or pilot lights were used to signal the operator, one for each circuit, if necessary. Installing pilot lights, or their equivalent, for all channels at each station of a random multiple access satellite system would require that each station select all channels by frequency selection or time-slot selection. Recognizing that this selection might be among thousands and by means of quartz filters or correspondingly expensive time-slot selectors, one sees that this would place something of an economic burden on light-traffic stations. It would be theoretically possible to scan all the channels repetitively but this approach also is apt to become complex and expensive. Moreover, the cost and demand for satellite circuits should eventually make it preferable to use them only for actual communication, rather than tying them up while their distant users are being connected. Thus, it seems probable (although not yet certain) that auxiliary "order" circuits should be used for calling, and also for system supervision and similar inter-station "service" communication. Such communication probably will be automatic and of a coded digital nature but it is conceptually convenient to assume that it is "human" communication between station operators.

In an early study it was assumed that the station operators would communicate over a single "party line" channel, since each would use this channel briefly and infrequently (see Fig. 5 of ref. 1). Such a channel was assumed in the discussion of Fig. 13. At the date of this earlier study the possible troubles introduced by the relatively long delays of satellite circuits were overlooked.

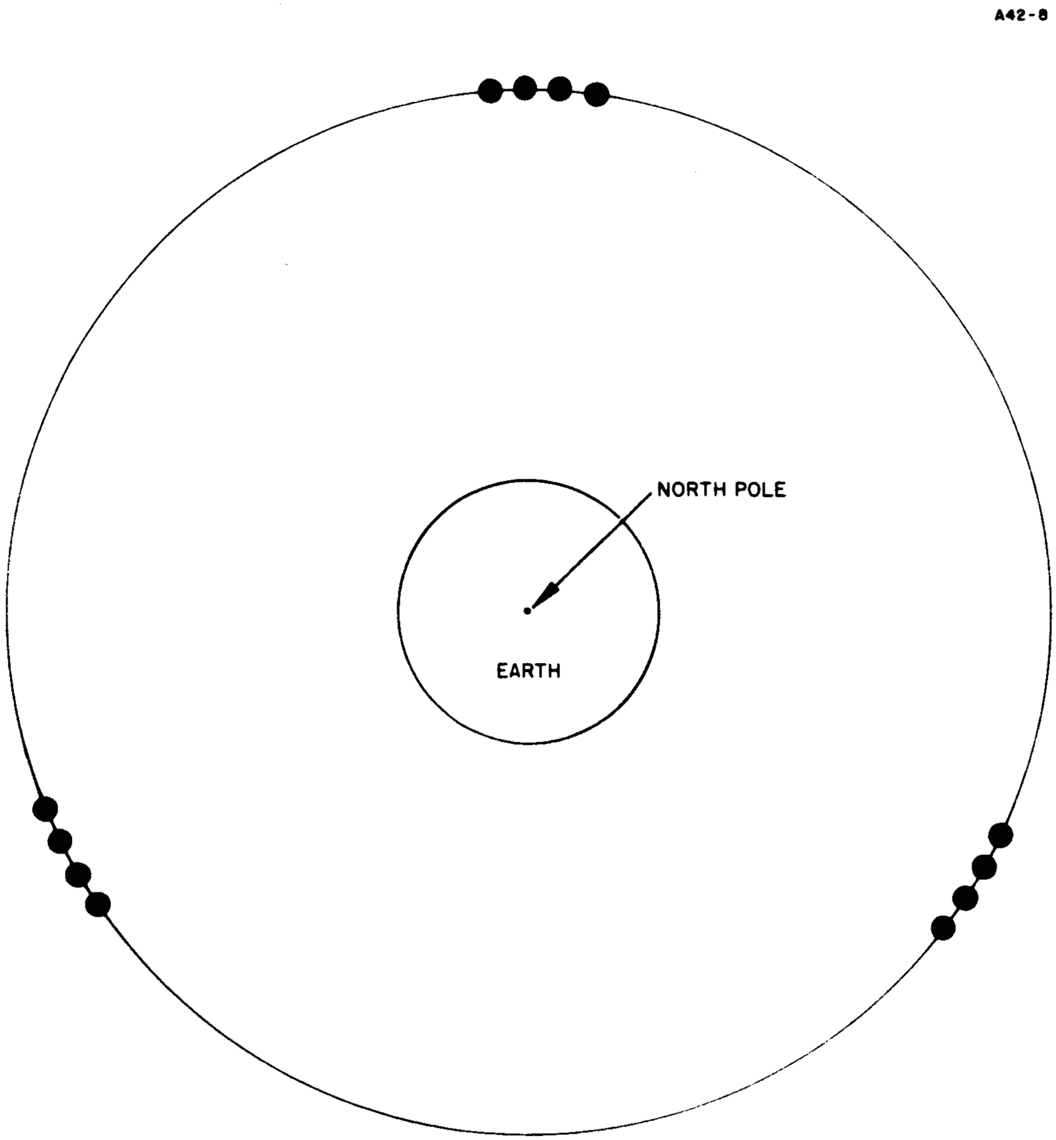

Fig. 16. Use of stationary satellites in clusters to increase system capacity.

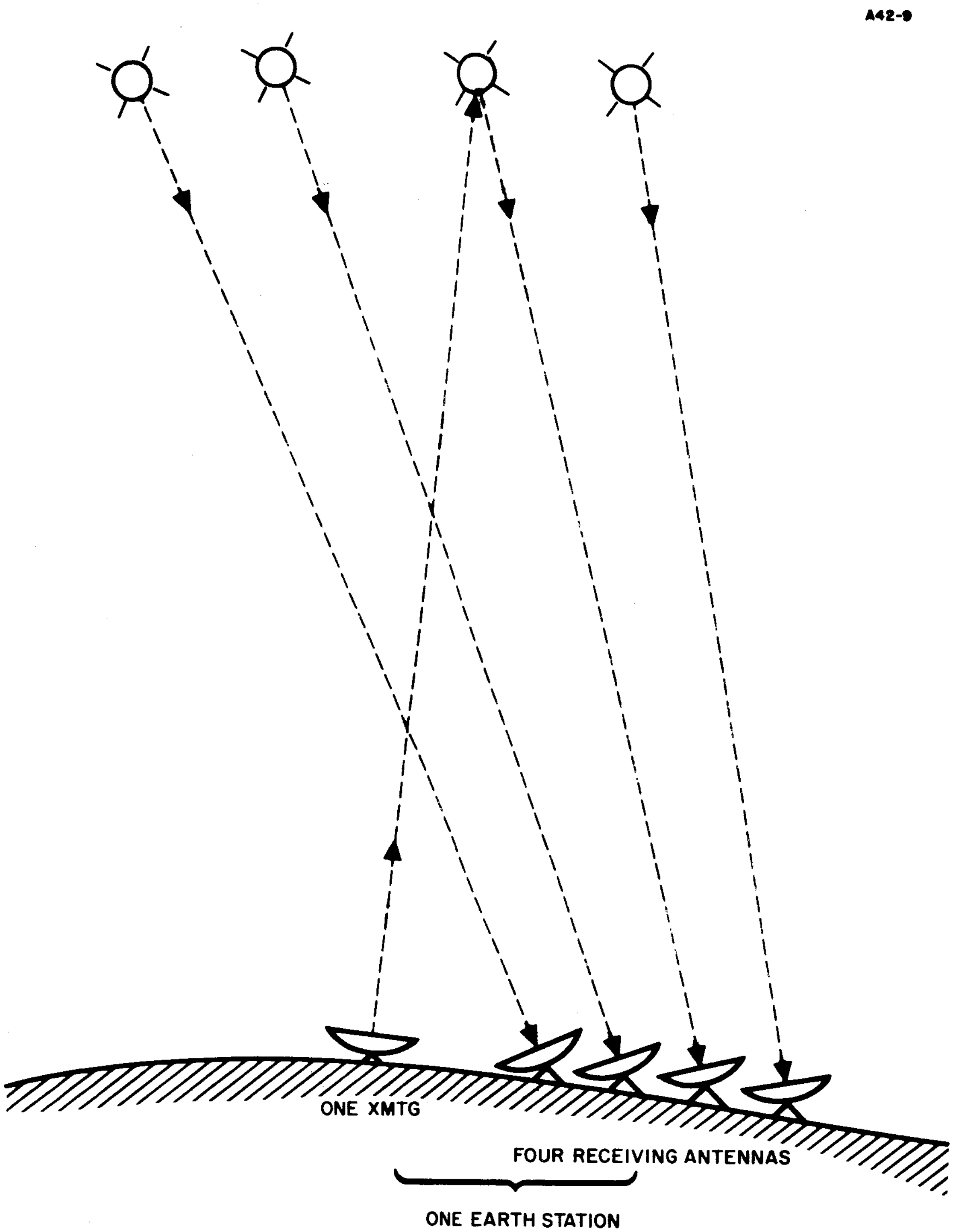

Fig. 17. Random access using four stationary satellites clustered.

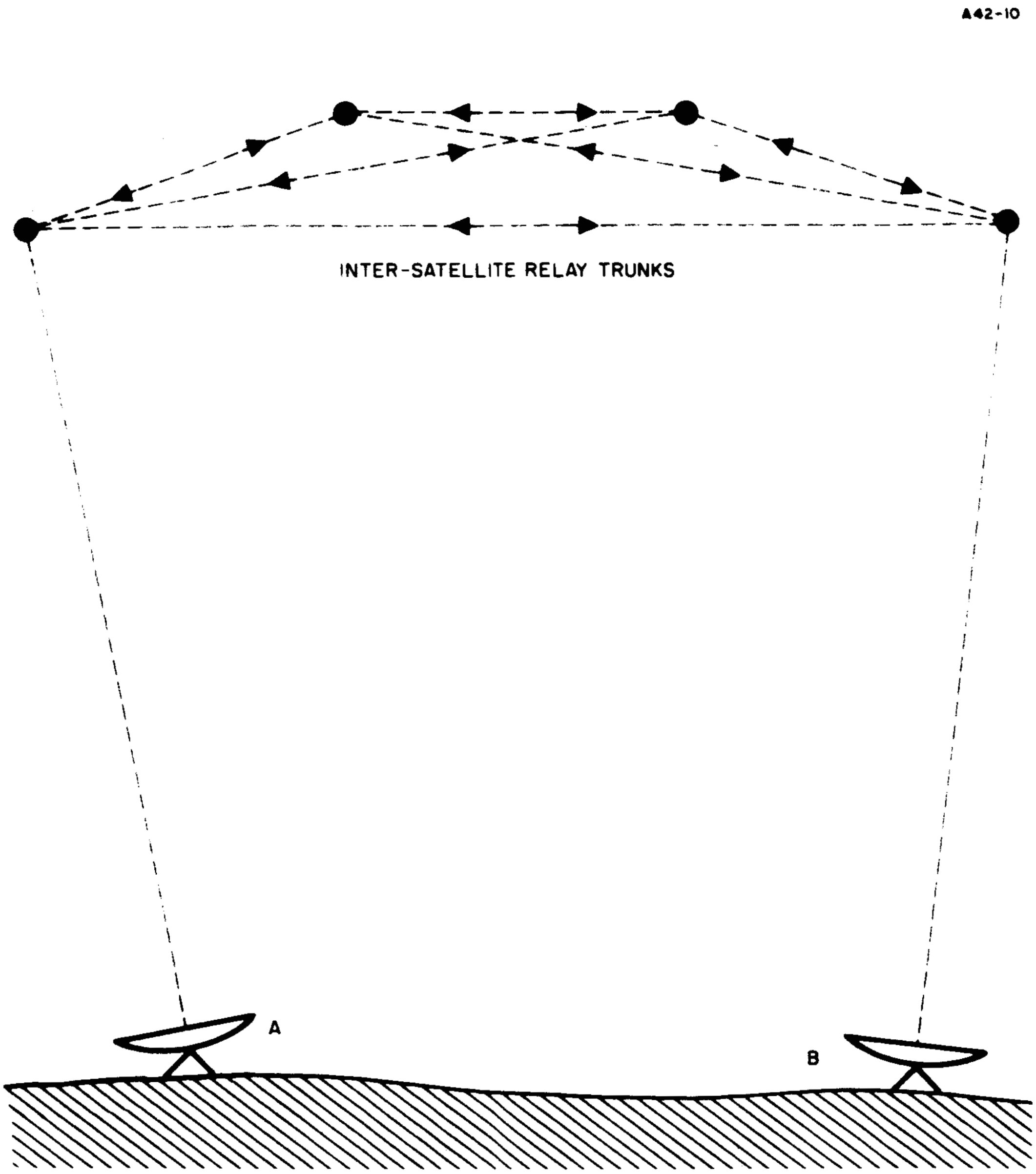

Fig. 18. Use of satellite cluster with inter-satellite relay trunks which permits each earth station to use a single satellite.

Assume that the up-and-back propagation time delay is only 0.1 sec, recognizing that with a stationary satellite it could approach 0.3 sec. The (automatic) operator at station A desires to call C and, hearing no other calls on the party line, assumes that it is available and makes the call. Some milliseconds earlier, however, B had started a call to D. Soon thereafter, as shown in Fig. 19, A hears B's call starting before his own call, while stations C and D receive the calls, unintelligibly overlapped. A had no way of knowing that B had started his call first. The probability of such self-jamming depends primarily on both the system capacity (mean calling frequency) and the delay. Illustratively, if such a call is required only once every ten minutes for each circuit in a 600-circuit system, there would be an average of one call per second. There then would be a 10% average probability of a call starting within any tenth-second period of delay hiatus. Unless the duration of individual calls could be reduced to the order of a millisecond, requiring that the order channel have more than voice bandwidth, the probability of call conflicts and the consequent confusion could be intolerable! The party line order circuit is conceptually nice but much in need of improvement.

There have been several approaches toward the elimination or reduction of call overlap jamming on a party line order circuit. The use of briefer calls over a broader channel has been mentioned. This approach only reduces the interference probability without eliminating it, and it is an approach which can become a bandwidth hog.

Another approach, illustrated in Fig. 20, is to transmit a short "priority pulse" simultaneously starting a delay-time gate on the receiving circuit. Receipt of one's priority pulse (as determined by the delay gate) ahead of a pulse from some other station permits initiation of the call. Prior receipt of another priority pulse inhibits the call and requires another try. Of course, there remains the slight danger of coincidence of priority pulses and the possible countermeasure of near-coincident pulse sensors, etc.

A different approach is to prefix calls with "hold" symbols longer than, say, twice the delay time, as illustrated in Fig. 21. In placing a call, station A transmits a sustained tone of an assigned and relatively high frequency as its "hold" symbol. If another tone is received prior to the delay time, it will inhibit A's call. If it arrives in coincidence with A's tone, the resultant beat tone inhibits both calls.

Related to the above approach is that of slowing down the calls so much that stations recognize calling conflicts during the first few information bits. This approach leads one quickly to calls whose duration (in excess of one second) would limit the system's circuit capacity, or at least limit its rate of circuit utilization. At this point one perhaps recognizes that such slow calling requires correspondingly little bandwidth, so a considerable number of calling circuits might well be used — but how?

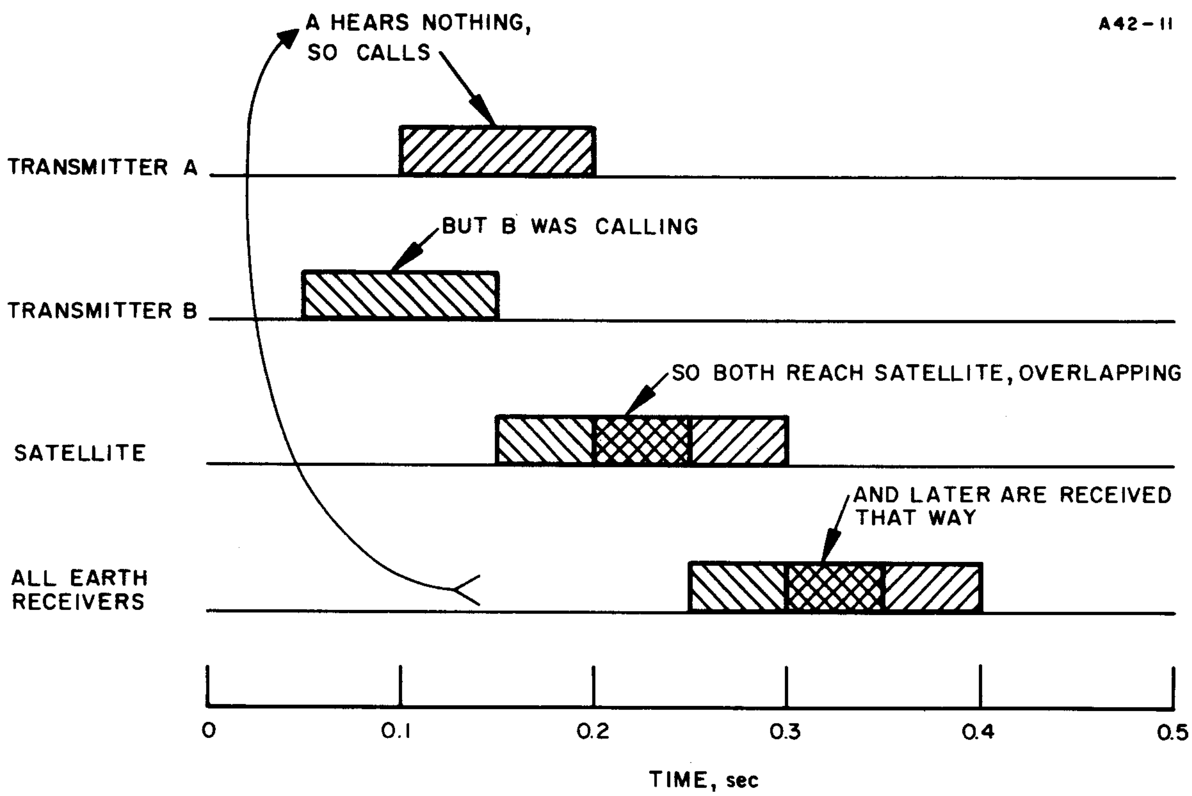

Fig. 19. Delay self-jamming with "party line" calling system. One way delay assumed to be 0.1 seconds for all stations.

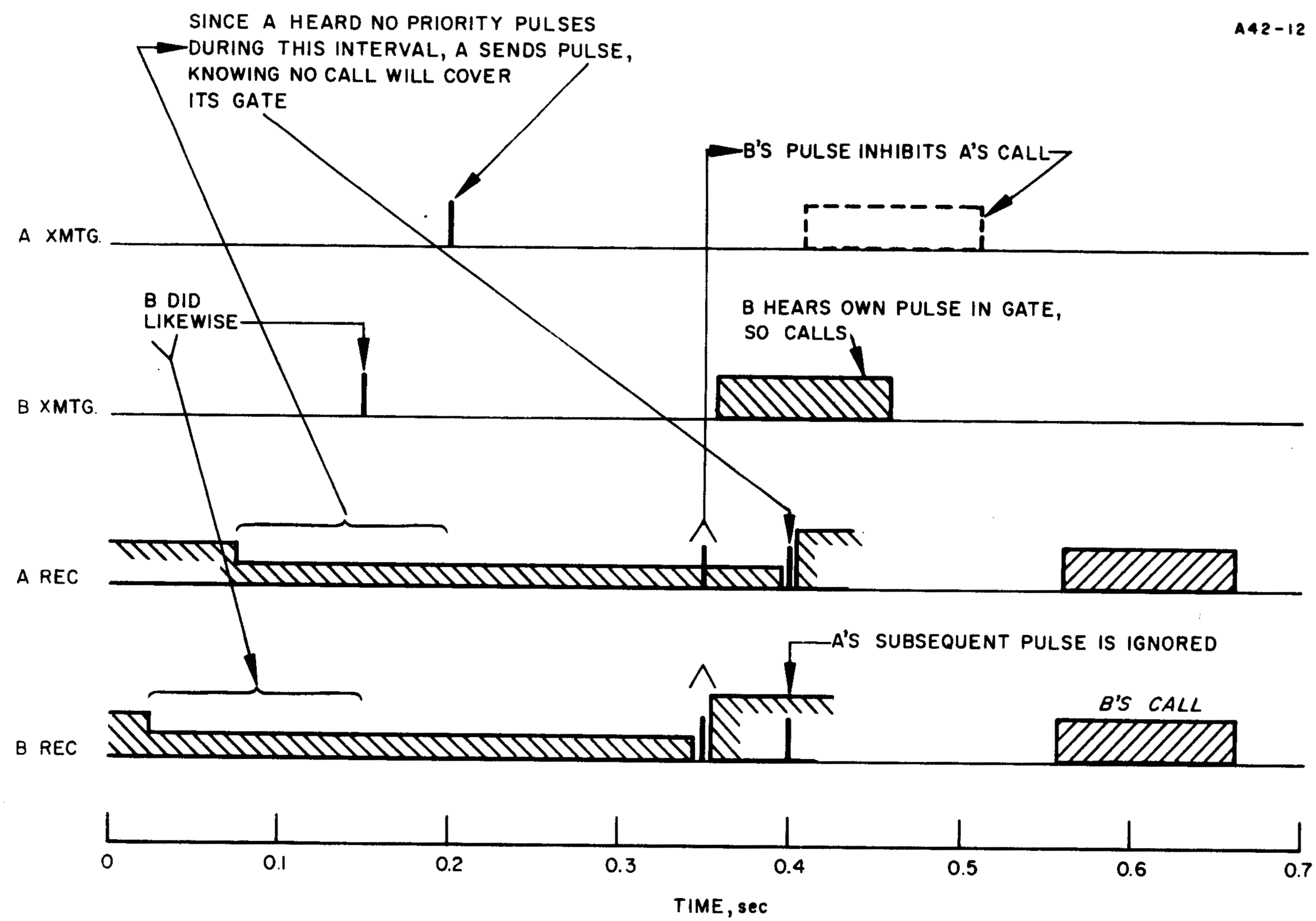

Fig. 20. Use of a priority pulse to avoid self-jamming.

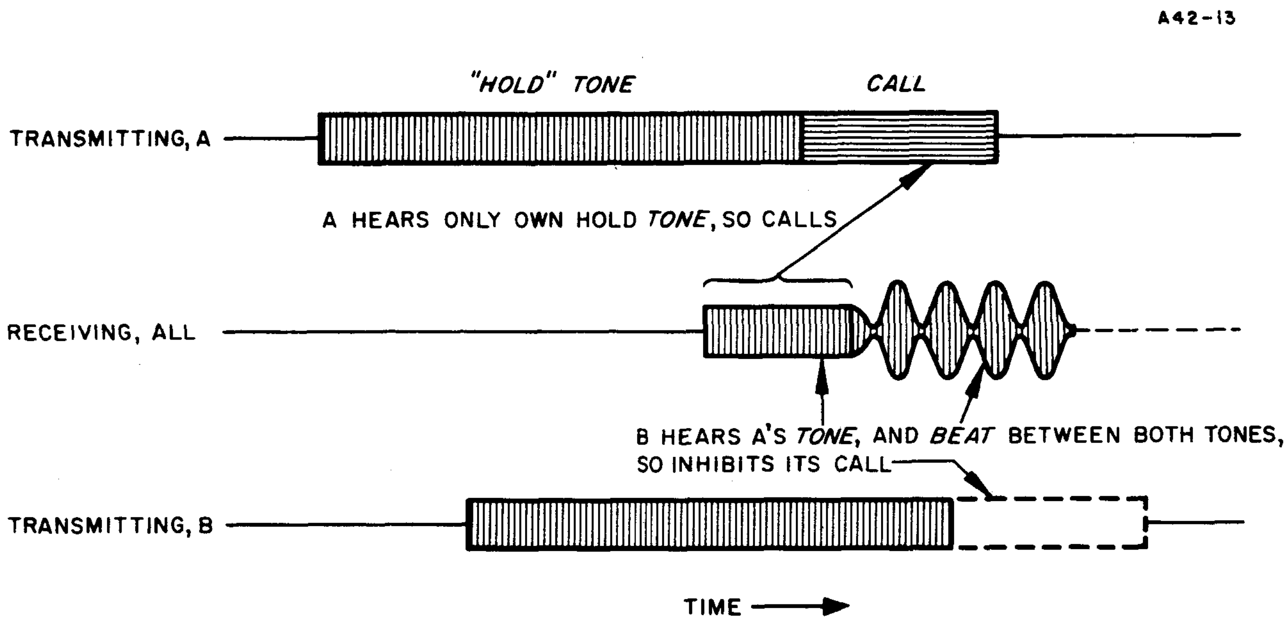

Fig. 21. Use of hold tone to avoid self-jamming.

The solution, which seems to have been proposed independently and in somewhat different forms by GT&E and ITT is illustrated in Fig. 22. Each station has its own narrow band (teletype) circuit to a "master control" station which keeps track of the system's circuit utilization and which assigns circuits for each "call," broadcasting these assignments to all stations over a sufficiently high speed (broad band) one-way circuit. The use of individual circuits to master control, with suitable "storage" recording with each such circuit, eliminates the difficulties from overlapping calls. Many such slow-speed calling circuits can be multiplexed over one or more voice circuits using either FD or TD multiplexing.

VII. OTHER FUNCTIONS OF MASTER CONTROL

One likely would provide a master control station for a multiple access system, whether or not it exercise tight control of circuit assignments, call by call, or lesser control of the transmitting circuits available to stations. For example, it would seem necessary for such a control station to monitor operation of the other stations to assure compliance with the system's technical standards. Otherwise, one station might raise the power level of its few channels to the detriment of other stations. Such monitoring may be possible by observing the satellite's re-transmitted channels with a spectrum analyzer. Alternatively, telemetry of performance data may become advisable.

In case of manual operation, master control would monitor and correct breaches of good operating practice, such as prolonged calling or unnecessary chit-chat over the party line, if one is used. With automatic operation, master control would detect malfunctions of calling or call-receiving equipment, should such occur. One strong related argument is that unforeseen emergencies are bound to develop even with the best automatized systems, and such emergencies call for the diagnostic and corrective help of human intelligence. Presumably, master control would never become completely automatized and devoid of this human intelligence.

Tight control could be advantageous for accounting reasons, since master control could keep detailed records of each station's use of the system. Such records would permit equitable allocation of system operating costs among its stations. Adequate records could perhaps be kept by the individual stations, or by a "loose" control station but record keeping by tight control would seem more satisfactory.

Which station should have master control? It need not be a "traffic" station. There are arguments that it should be the station which also has responsibility for satellite station keeping and other control of the satellite(s).

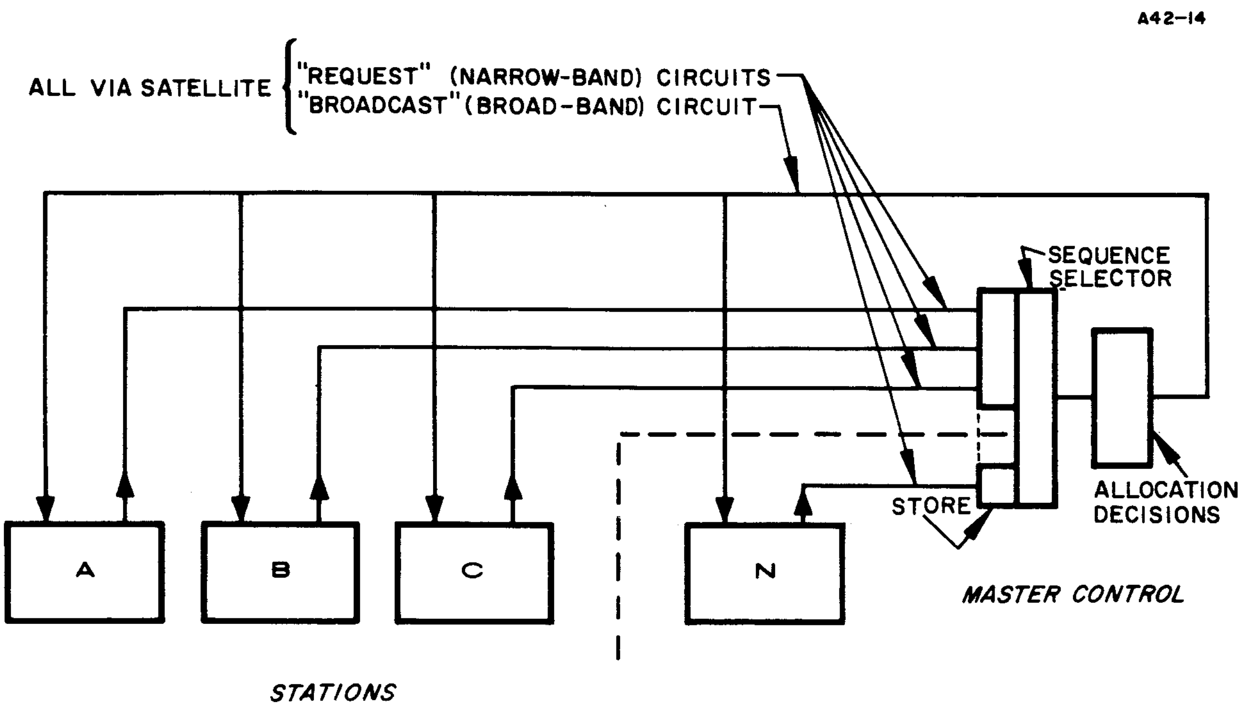

Fig. 22. Calling by use of individual "request" circuits to master control.

Such a station also could broadcast tracking corrections, as needed, and exercise control in anticipation of eclipse interference conditions with other co-channel satellite systems. Thus, it would become the focal point for inter-system coordination, when needed. Another seemingly unrelated argument is that the station having the heaviest traffic load should be the master control, because this would provide more direct control of the system's heaviest load. This argument seems relatively weak. However, it is possible that such a heavy-traffic station might also be the station in control of the satellite(s) and responsible for inter-system coordination. If so — good.

The writer admits, somewhat regretfully, that a tightly controlled random access system of 600 or more channels will need to be an automatized system and that its master control will need a digital computer. There is a lamentably expensive tendency to incorporate digital computers as an easy (?) cure-all for system problems, or perhaps as a status symbol of the system's sophistication. However, manual operation could become too slow and too difficult to coordinate, particularly in regard to optimum utilization of the few remaining available circuits during traffic peaks. One operator could not receive calls and assign circuits at rates of once a second or more. Several operators would be required, and they then might make duplicate assignments or similar errors. It seems clear that a computer memory could keep close track of circuit utilization and thus make better circuit assignments according to relatively simple programmed logic.

VIII. COMBINATION OF RANDOM AND PERMANENT ALLOCATIONS

One recognizes the use of "leased circuits" in present surface communication systems and the probable demand for such circuits in future satellite systems. The problems of providing leased circuits from a controlled random access satellite system should be inconsequential — little more than the equivalent of tagging these circuits "in use, hands off!" Additionally, use of such circuits could be programmed for certain hours only.

Leased circuits are similar to two-terminal "trunk" circuits and vice versa. Thus, some part of the circuit capacity of a random access system could be allocated as more or less permanent trunk circuits between terminals having essentially continuous traffic. Such trunks clearly are advantageous when they can be used heavily. Calls via such trunks need not be processed by the auxiliary calling circuits and master control.

There have been divergent estimates of the relative need for random access and trunk circuit capacity, with some estimates indicating a nearly exclusive need for trunks. It is believed that such estimates are

unreliable, except in relation to the restrictive assumptions on which they are based. A system serving only a few major population centers, having well defined traffic flow patterns, would have little need for random access. A system having many small stations and less defined traffic patterns would have great need for random access.

The point worth remembering is that random access provides flexibility and freedom for growth, but the full flexibility need not be used. A random access system can provide permanent trunk circuits, as needed, but a permanent trunk system cannot provide the ability to use a circuit between one pair of stations for one call, then between a different pair of stations for the next call.

IX. SOME ECONOMIC ASPECTS

The economic aspects of multiple access are probably more important than the technical aspects, because certain aspects or features could be technically possible but economically ruinous. Present cost estimates for satellite communication systems are notoriously nebulous, as one might expect. Thus far, the system specifications and experience are inadequate. Hence, it seems more useful to seek economic principles (and the guidance of such principles) and to regard dollar estimates only as being relatively illustrative.

One such principle is that satellite communication will have some break-even distance in relation to any specific surface communication technique. This principle can be useful even though we cannot yet express (or agree on) mileages. The significant fact is that the cost of one-hop satellite communication should be essentially independent of distance, whereas all surface communication costs increase with distance. One use of this principle is in directing satellite system development toward reduction of these break-even distances, thus increasing its competitiveness and usefulness.

Another such principle is that satellite communication will have some break-even volume, in relation with surface communciation, especially beyond the break-even distance. Actually, it will be seen that these two break-evens are interrelated but that the volume break-even may determine the economic feasibility of random multiple access satellite systems.

Early economic studies led to the conclusion that satellite communication would be limited to heavy-traffic earth stations, with two such stations utilizing the satellite's channel capacity. Should this always be true, multiple access satellite systems would have a serious economic

handicap. Actually, many of these early studies were too constrained to the state-of-the art, or to the state of thinking, and they failed to isolate basic cost factors and study their reduction, or to define development paths which should reduce the volume and distance break-evens.

The cost of satellite communication will depend on the total system costs-satellite plus earth stations. Neglect of this has led advocates of passive satellites to claim "most communication per dollar in orbit," neglecting the excessive earth station costs of passive systems. Nonetheless, it can be useful to study means of reducing earth-station costs, to the extent that possible effects on over-all costs are not neglected in a final analysis. As a subsequently discussed example, earth station costs can be reduced by the use of fixed antennas, requiring the use of stationary satellites. One or a few such satellites in orbit should not cost much more, and probably less, than the larger number of individually less expensive non-stationary satellites. Since the use of fixed antennas could reduce earth-station costs significantly, their use by the many stations of a multiple access system should reduce the total system cost, irrespective of any probable difference in satellite costs.

Bearing the above in mind, it can be useful to classify earth-station cost elements in order to reach a significant conclusion. Some elements of cost tend to be proportional to the number of circuits. Channel selectors, compandors and echo suppressors are examples because one per circuit is needed. Other cost elements tend to be fixed, or at least not necessarily directly related to the number of circuits. The cost of antennas, buildings, land, etc., are good examples. One notes, however, that it might require a larger and more expensive Quonset hut to house 600-circuit station equipment than to house equipment for only six circuits. Moreover, a Quonset hut might be used for a seldom seen 6-circuit station, whereas the 600-circuit station's building might be a marble show place. On the other hand, some newly developing nation might regard its little station as a national monument to its space age progress and erect a station building with suitable accommodations for its entire Telecommunications Administration! Some "fixed" costs are exasperatingly elastic.

Some costs, such as that of transmitters, are uncertain functions of the number of circuits. Negligible increase in peak power capability would be required, up to perhaps 100 circuits, whereas beyond perhaps 200 circuits, the peak power would increase linearly. Additionally, transmitter power and cost are not directly related; the first kilowatt is more expensive than the tenth. Nonetheless, transmitter and similar costs can be approximated usefully by the constant and first power terms of a power series, as a fixed cost plus the total per-circuit cost.

Figure 23 now illustrates the obvious; if the fixed costs are high, many circuits are needed if the total cost per circuit is to be reasonable. Lowering the fixed costs reduces the number of circuits required for similar total cost per circuit. Hence, reduction of fixed costs of earth stations is the key to economic feasibility of multi-station random access satellite communication.

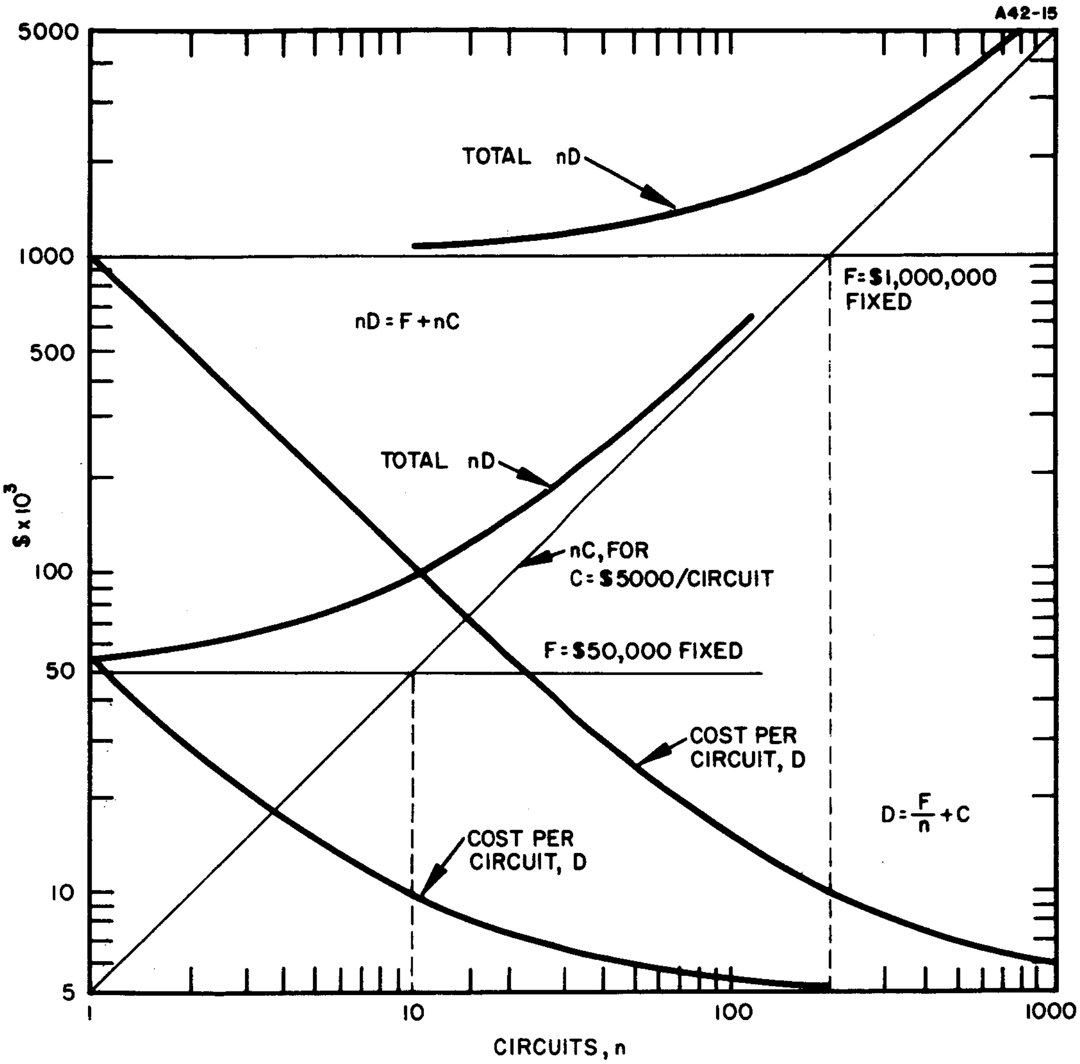

Fig. 23. Illustrative earth station cost relations.

Before trying to turn this key, however, let us briefly examine a possible future interrelation between satellite and earth station costs. Assume that helium cooled masers permit a receiving system noise temperature of $50^{O}K$ at a cost of $50,000 each, whereas $5,000 parametric amplifiers would permit operation at $200^{O}K$ requiring 6 dB stronger signals. With a system of, say, one stationary satellite and 100 earth stations, use of parametric amplifiers would save nearly $5,000,000, whereas a 4 x increase in the satellite's transmitter power might cost less.

One needs to adjust the satellite and earth costs for minimum system costs.

Much of the above discussion has been over-simplified in interests of clarity. For example, we have implied a concentration on capital investment, rather than annual per channel costs, much as if satellites were as reliable and durable as earth stations. Today, we might need to keep orbiting stationary (or other) satellites, as fast as we could afford, in hopes of having spares in orbit in time to replace total failures. Perhaps increasing the satellites's power would shorten its life so much as to cancel the savings on masers. Satellite reliability is still a very real and serious problem.

Nonetheless, it is a state-of-the-art problem which should be a continuing challenge, but not a permanent obstacle.

Satellite costs need to be studied more thoroughly, perhaps on a basis similar to that used in Fig. 23 for studying earth station costs, except for the greater necessity of studying per year costs. Perhaps a three term power series approximation will be needed. Certainly there will be some constant term or minimum cost of placing "no-circuit" (minimum weight) satellites in orbit. The additional weight required to relay a few circuits probably would not increase this cost significantly, but the cost per circuit would be high. Some larger number of circuits certainly would double the satellite costs but lead to a lower "balanced" cost per circuit. If one were to push the state-of-the-art by trying to relay too many circuits, a second-power cost term probably would come into play and increase the cost per circuit. The coefficients in any such power series approximation to satellite costs certainly will change as the art advances. Reliability improvement could change these coefficients most rapidly from whatever values they may have today.

It is to be hoped that satellite system costs will be such that the service charge per circuit year will be in balance with earth station costs per circuit year, based on an economic (cost balancing) number of circuits per station. Excessive satellite service costs would favor the use of fewer circuits per station, but this condition should focus attention on satellite system cost reduction.

Whenever over-all system cost curves can be prepared, along lines such as illustrated in Fig. 23, we can start assigning meaningful numbers to the distance and volume break-evens and thus become able to recognize (and improve) the competitive applications of satellite communication.

X. EARTH STATION ANTENNAS

Earth station antennas constitute an excellent example of the elasticity of cost estimates. If one specifies only a "steerable antenna with at least a 60-ft aperture" one can obtain costs ranging from about \$10,000 to \$15,000,000. The first figure applies to the cost to Stanford Research Institute of a light 60-ft parabolic reflector antenna on a very simple pedestal, excellent for tropospheric propagation research but totally inadequate for satellite communication. The higher figure is the reported cost of the Andover station, built for use with TELSTAR. This cost probably contains development costs and certain nonantenna costs. Perhaps copies of its 3,600 sq ft horn-reflector antenna and radome might cost \$5,000,000 or less. Parabolic antennas of 60-85 ft aperture with surface accuracies which are adequate at 6 Gc and on precision tracking pedestals seem to be within the \$100,000 to \$1,000,000 price range. Even when such antennas are diplexed, two are required (today) for hand-over and a third is advisable as a spare. Thus, with nonstationary satellites, a station's antenna costs are at least on the order of \$1,000,000. At this point, small and impoverished nations lose interest in satellite communication, beyond hoping that our use of satellites will cause us to release HF radio channels for their use!

These tracking antenna costs become the controlling fixed cost for earth stations using nonstationary satellites. Other fixed costs also tend to rise, if only because they are masked by the antenna cost. With such expensive antennas it would seem inappropriate to economize on a Quonset hut or on paving of the access road!

Turning back to Fig. 23 and assuming $F = \$1,000,000$ fixed costs, one sees that 200 circuits are required to obtain $D = 2\ C =$ \$10,000 per circuit.

On such a cost basis, multiple access would not become attractive until high-capacity satellites could be used by a number of 200-circuit stations. Today, relatively few population centers would generate enough traffic for 200-circuit stations. Note, however, that this conclusion rests on the high costs of <u>steerable</u> antennas, for use with <u>nonstationary</u> satellites. The conclusion <u>should</u> be that we should <u>reduce fixed costs</u> and thus make random access satellite communication attractive to smaller population centers, especially to centers in those areas of the world where modern communication is lacking and most needed. Bring satellite communication to those who need it, instead of just waiting until they can afford it in 200-circuit chunks!

Large fixed-reflector antennas can be relatively cheap, especially if they are earth-supported concrete structures built somewhat like "California swimming pools." Figure 24 shows one possible configuration,

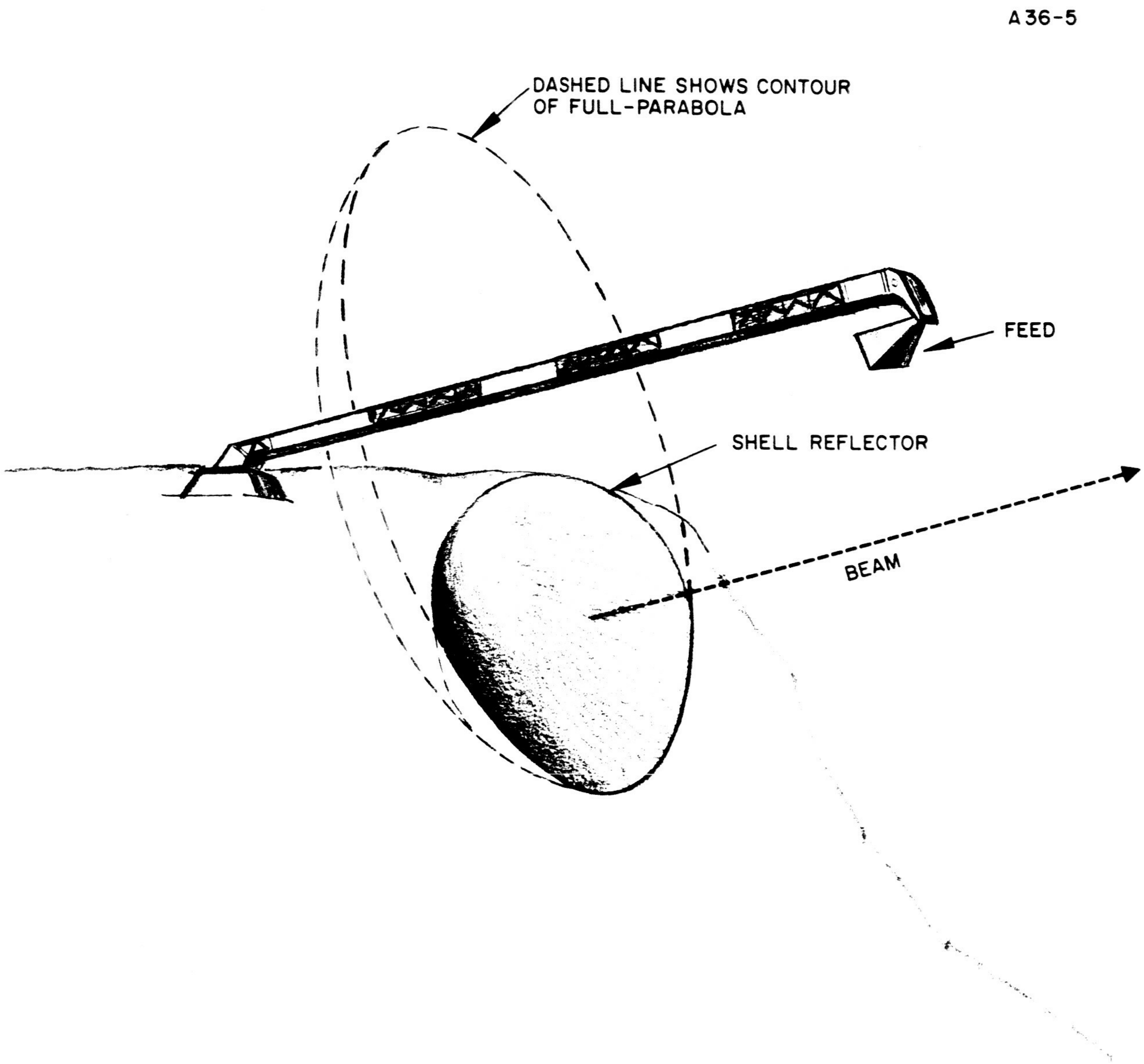

Fig. 24. Shell reflector for a low beam elevation angle.

employing a "shell" sector of a paraboloid set into a relatively steep hillside to obtain a low beam elevation angle to a stationary satellite which is correspondingly close to the horizon. The cost of such an antenna cannot yet be estimated accurately, but it seems safe to predict that it should be less than 10% of the cost of a comparable full tracking antenna. Moreover, only one per station would be required because stationary satellites eliminate hand-over.

"But will stationary satellites be sufficiently stationary?" Probably not at first, but later ones certainly will be. The first ones may stay within only a degree or so of their station but later ones may be held within a tenth-degree or less, if necessary. Actually, some beam steering from the feed point should be possible with these fixed antennas. How much and how to do it have not yet been determined adequately.

Concrete earth supported antennas have other attractive potentialities, such as "hardening" and the possibility of "breaking the gain barrier" by obtaining more accurate and stable surfaces. However, their major importance relative to multiple access satellite systems is that of fixed-cost reduction, as seems essential if light load stations are to become economically attractive. The corollary conclusion, like it or not, is that stationary satellites are equally essential.

XI. FREQUENCY SHARING ASPECTS OF MULTIPLE ACCESS SYSTEMS

Little discussion of the frequency sharing aspects of multiple access systems seems warranted at present. The potential frequency sharing advantages of stationary satellites are gaining recognition. The potential surface interference advantages of earth supported fixed reflectors seem obvious; they at least should have weaker back-lobes!

A thus-neglected advantage may be the possible reduction of interference to microwave receivers. Each station would transmit only its fraction of the power received by the satellite, and this on relatively few voice bandwidth (SSB) channels which perhaps would be grouped. Stations having local interference problems might be assigned the less troublesome frequency channels. Also, microwave systems which are not fully loaded might avoid use of the interfered-with channel.

On the negative side, SSB transmissions probably will require higher power per channel.

XII. CONCLUDING COMMENTS

This report represents a rather hasty effort to survey what now is known (or thought) about multiple access satellite systems. Its purpose is to serve as an introduction to how we may (and should) soon use communication satellites as if they were "exchanges in orbit."

The treatment has deliberately been kept descriptive and non-mathematical to enhance its readability and, incidentally, to leave problems for others to explore more deeply and rigorously. Others already have explored various facets of multiple access technology with commendable thoroughness and it is regretted that all such work has not been referenced, discussed and related to the over-all problems. Except for a rather brief and inadequate CCIR document, ref. 10, there appears to have been no prior attempt to survey the possibilities and possible problems of this class of satellite communication systems. It is hoped that this report will help others to understand such systems, and then stimulate them to increase this understanding.

Descriptive introductions, such as this, make it difficult to avoid expressing opinions, rather than facts. Some of the writer's opinions are not shared by others. It is hoped that conflicting opinions (<u>or</u> facts) will be brought out so that differences can be resolved.

Multiple access systems and particularly random access satellite systems hold the potential of revolutionizing the prior paired-terminal trunk philosophy of long-haul communication, the philosophy of bringing the communication traffic to a few "gateways," rather than bringing these gateways closer to the traffic sources. We are just beginning to recognize the revolutionary aspects of possible intercontinental "central exchanges," such as one for the <u>five</u> continents (including Antarctica) of the Atlantic Basin.

Much work remains to be done — too much to be outlined adequately here. For example, the SSB-up-FM-down may (or may not) be the best modulation and multiplexing approach. It seems to be the best. However, a good way to find out, <u>before</u> orbiting satellites, would be to set up and thoroughly test <u>adequate</u> simulations of the proposed system or competitive ones. Doubtless such simulation will disclose unsuspected weak links, needing to be re-forged or replaced. For example, are present compandors satisfactory or is excessive reliance being placed on them for signal-to-noise improvement?

Without question, the time has arrived when a more thorough and widespread knowledge of multiple access satellite communication is needed.

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